variably saturated subsurface porous media. They do not represent true streamlines. In other words, these streamtraces represent "photographs" taken at specific times. Figure (6.1) shows that for a M&M weather condition and for a CONTROL harvest treatment, water flows from the flatwood into the pond (i.e., groundwater discharge) during the winter time due to gradients of hydraulic head. However, during the summer time the pond recharged the flatwood (Fig. 6.2). Streamtraces in Fig 6.2 show arbitrary fluid flow paths as surface water in the cypress pond subirrigate the surrounded pine forest in response to hydraulic head gradients.

These hydrological findings demonstrate that surface water contamination does not pose a problem during mean (M&M) or dry (H&D) weather conditions for partial harvest of the pine forest and that solute movement to the pond occurs only during periods of high water table when net water flow occurs from the flatwood to the pond.

Solute Transport in the CPFF

A major obstacle in studying contaminant transport in CPFF systems in the field is the complexity of the surface and subsurface flow domains and a limited understanding of the interdependence of the different hydrological parameters of the system. The water flow simulations revealed that during times of high water table there is a tendency for the water to flow from the flatwood toward the pond (i.e.,

APPENDIX

ENVIRONMENTAL IMPACT OF UNHARVESTED FOREST BUFFER ZONES UPON CYPRESS-POND SYSTEMS IN COASTAL PLAINS REGIONS: MODELING ANALYSES

By

ALI FARES

A DISSERTATION PRESENTED TO THE GRADUATE SCHOOL
OF THE UNIVERSITY OF FLORIDA IN PARTIAL FULFILLMENT
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I dedicate this work to my wife Samira, my mother Hassnah, my father Ahmed, my brother, my sisters and my children, who contributed to my success and well being.

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Abstract of Dissertation Presented to the Graduate School
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ENVIRONMENTAL IMPACT OF UNHARVESTED FOREST BUFFER ZONES UPON CYPRESS-POND SYSTEMS IN COASTAL PLAINS REGIONS: MODELING ANALYSES

By

Ali Fares

December 1996

Chairperson: Robert. S. Mansell
Major Department: Soil and Water Science

Hydrological and environmental impacts of tree harvest in flatwood pine forests were investigated using modeling analyses. A two-dimensional mathematical model was used to predict surface and subsurface water flows and contaminant transport in individual cypress-pond-flatwood-forest (CPFF) systems. Published field data from individual cypress ponds located in a CPFF in north central Florida successfully validated the model.

Hydrology of the CPFF system is primarily controlled by potential net water input (NWI = P-PET), simply defined as the difference between precipitation (P) and potential evapotranspiration (PET). Periods of groundwater recharge in the flatwood forest tended to be associated with NWI < 0 whereas flow into the cypress pond tended to occur when NWI > 0. The volume of surface water in the pond expanded during periods when NWI increased and shrank when NWI decreased with time. Magnitudes of NWI within a given year as well as between years were shown to be important to local hydrology. A "mean" weather year based upon 91 years of data provided a potential net water input of -155 mm yr^{-1}; whereas "wet and cold" and "hot and dry" extreme weather years provided +732 and -766 mm yr^{-1}, respectively. These three weather years were used to simulate the hydrology for unharvested, completely harvested and partially-harvested CPFF systems. For a given weather year, harvest of mature pine trees was shown to dramatically influence local hydrology by decreasing NWI and increasing surface runoff.

Contaminant simulations for intact forest over annual periods revealed that major contamination of water in the cypress pond occurred only during the "cold and wet" weather years. Negative net water inputs for "mean" and "hot and dry" weather years greatly minimized the potential for contamination of pond and runoff waters. Maximum potential for contamination of cypress ponds occurred after complete harvest of flatwood pine trees due to drastic decreases in system ET. During a mean weather year, unharvested buffer zones surrounding a pond during 75% harvest of the pine forest provided significant control of contaminant movement to the pond.

CHAPTER 1
INTRODUCTION

Research Background

Water managers have long recognized that major changes in forest conditions greatly affect water use in local streams and lakes. As early as 1600 BC, Emperor Yu of China implemented a forest management program aimed at controlling erosion and floods (Brown and Beschta, 1985). The slogan for his national program was "to protect the river, protect the forest." Early Greek scientists/philosophers similarly realized that water flowing through a forest was much better for drinking purposes than water in agricultural areas.

Increasing demand for wood fiber for paper products and limitation of additional land areas for planting to forest species has resulted in intensified forest management practices (silviculture). Additionally, marginal lands where an interface occurs between terrestrial and aquatic ecosystems are sometimes used. Intensive management practices in these relatively sensitive environments such as the coastal flatwood landscape in north central Florida have generated concerns about effects of forest practices on the quality and quantity of surface water in adjacent wetlands and ground water of the whole system. Harvesting operations in forests such as thinning and partial cuts cause a moderate increase in water yield, whereas clear-cuts maximize flows out of the forest (Moore, 1988). Augmentation of water flow naturally varies from site to site and from year to year. Recently, alternative management practices such as maintaining unharvested buffer strips around surface water bodies (lakes, rivers and ponds) have proven to be valuable agents in mitigating the impacts of agricultural practices on surface and ground water quantity and quality (Moore, 1988). However, relatively few studies have examined the effectiveness of buffer zones for mitigating the effects of silvicultural practices (Nutter and Goskin, 1988).

Hydrologists are often requested to describe and interpret the behavior of these forest systems. Although some conclusions can be made using best engineering and biological judgment, in many instances human reasoning alone is inadequate to synthesize the conglomeration of factors involved in analyzing complex hydrological problems. Field experiments can be conducted to answer many of these practical questions; however, such investigations are commonly site specific, dependent upon climatological conditions, and costly in time and resources.

Mathematical models based upon sound physical theory can provide an alternative tool for assisting hydrologists to meet the challenge of description and interpretation.

Hydrological modeling combines the subtlety of human judgment with the power of a digital computer (Anderson and Woessner, 1992). Mathematical models allow more effective use of available data and can account for more complexity (Hamilton, 1982). Such models have expanded current ability to understand and manage water resources (Friedman et al., 1984). Hamilton (1982) added that mathematical models, in some cases, have increased the accuracy of estimates for future events to a level beyond "best judgment" decisions. Mathematical models are essential in performing complex analyses and in making informed predictions concerning consequences of a proposed action.

Models can be used in an interpretive sense to generate insight into the controlling parameters in a site-specific setting or as a framework for assembling and organizing field data and formulating ideas about system dynamics (Anderson and Woessner, 1992). Modeling provides an excellent means to help organize and synthesize field data but it is important to recognize that modeling is only one component in a hydrological assessment and not an end within itself. Reliable field data are essential when using a model for predictive purposes. However, attempts to model a system with inadequate field data can also be instructive as they may serve to identify those areas where detailed field data are critical to the success of the model (Wang and Anderson, 1982.

Cypress swamps are the major deepwater forested wetlands in the USA (Mitsch and Gosselink, 1986). These swamps are intimately mixed with flatwood forest plantations. Because of the perception that water and nutrients move into the swamps from the entire surrounding flatwood area, there is concern that forest management of the uplands could result in changes in the water or nutrient regimes in the swamps, which may eventually affect plant community structure or biodiversity (Crownover et al., 1995).

Field experiments have been conducted to evaluate alternative forest management practices; however, such studies are typically site specific, weather-dependent, and costly in time and resources. Recent advances in computer simulations of groundwater movement, solute transport, and solute sediment interactions have provided useful research tools to model the hydrogeologic complexity of wetland systems (Richardson et al., 1994). Models offer practical tools for optimizing two precious assets: time and money (Salama et al., 1993). Modeling endeavors may lessen the number of field experiments required to implement and underscore major parameters and variables that most influence this system. Models should also be utilized to plan the design and operation of hydrological field experiments in flatwood forests. Once hydrological parameters for flatwood systems are specified, future field work can be dramatically reduced and these parameters can be realistically quantified, and the overall system response can be determined.

Hypotheses

Two hypotheses provide the basis for this research investigation. The first is that major aspects of water flow and solute transport between cypress ponds and surrounding flatwood pines forests can be simulated using a computer model. The second hypothesis is that unharvested forest buffer surrounding cypress ponds can be effectively used to minimize the contamination of the pond water with herbicides and fertilizers applied to the forest.

Objectives

This investigation is focused upon describing the effective interaction of hydrological processes linking individual cypress ponds and their surrounding flatwood pine areas with respect to the use of unharvested forest buffers. Specific objectives of this research include

1) To verify and utilize a mathematical model as a low-cost means for describing complex water flow and chemical transport fluxes within the interfacial transition zone between a cypress pond and a surrounding flatwood forest.

2) To utilize the model to predict the hydrological and water quality responses of a forest wetland system to an

unharvested buffer zone surrounding individual cypress ponds.

Structure of the Dissertation

Six chapters are included in this dissertation. A literature review presented in Chapter 2 provides i) a comprehensive overview of the hydrology of the cypress pond flatwood forest system (CPFFS) and ii) a synthesis of information about current and alternative management practices such as the use of unharvested buffer zones proposed for forest wetland systems. Chapter 3 describes the WETLANDS model and discusses the theory of twodimensional numerical modeling of water flow, and solute transport in a variably-saturated subsurface porous medium that is dynamically linked to surface water bodies. Chapter 4 describes a prediction submodel based upon the Priestley-Taylor equation for estimating the potential evapotranspiration for multi-dimensional water flow in soils. This submodel is utilized in conjunction with WETLANDS model for water flow and solute transport in soil. In Chapter 5, the WETLANDS model is utilized to evaluate the effects of the tree-harvesting strategies, precipitation, and potential evapotranspiration on the hydrology and the solute transport within the CPFS. Chapter 6 covers the discussion of simulation results and their practical implications on the hydrology and water quality of the CPFS.

CHAPTER 2
HYDROLOGICAL ASPECTS OF CYPRESS WETLANDS IN COASTAL REGION PINE FORESTS AND IMPACTS OF MANAGEMENT PRACTICES: LITERATURE REVIEW

Introduction

Wetlands, as defined by the U.S. Fish and Wildlife Service, are lands transitional between terrestrial and aquatic systems where the water table is usually at or near the surface or the land is covered by shallow water (Mitsch, 1979). Two important hydrologic factors, climate (rainfall and evapotranspiration) and topography, interact to explain the existence of wetlands in any landscape (Zoltai, 1988). Depressions tend to collect water. Relatively level areas do not have enough slope to create appreciable runoff and low areas including floodplains receive runon water from adjacent uplands in addition to periodic flooding.

Cypress (*Taxodium ascendens* Brongn.) ponds, also called cypress swamps, the major deepwater forest wetlands (Mitsch and Grosselink, 1986), are permanently wet depressions in the landscape. Cypress ponds fluctuate in area and depth during different seasons of the year. These ponds are numerous in the flatwoods of much of the lower Atlantic and Gulf Coastal Plain provinces of the southeastern U.S.

(Crownover et al., 1995). Improved understanding of the complex interaction of hydrological processes in transition zones between cypress ponds and associated flatwood pine areas is a prerequisite to quantifying the environmental impact of management practices on these systems. The use of vegetative buffer zones or riparian strips has been suggested to provide environmental protection for these wetlands. Such buffer zones can be created by leaving unharvested trees around individual cypress ponds during the harvest of mature pine forests.

Cypress swamps and cypress swamp hydrology have been the focus of several field investigations (Riekerk et al., 1995; Sun, 1995). Some of these experiments targeted the use of cypress swamps as waste water treatment localities (Ewel and Odum, 1984; Gillespie, 1976; Heimburg, 1976). Other field experiments have addressed the magnitude of ET from the ponds and the impact of clearcutting upon the ET of the area (Liu, 1996; Ewel and Smith, 1992). This chapter provides a comprehensive review of the hydrology of the CPFS, and a synthesis of information concerning current and alternative management practices proposed for such systems.

Hydrology of Cypress Pond Flatwood Pine Systems

Determining water budgets for wetlands is an imprecise task because of difficulties associated with determining each of components and because of the climatically controlled temporal fluctuations of wetland hydrology (Carter, 1986). High uncertainty typically occurs in experimentally determined water budgets for wetlands due to difficulty in determining the magnitude of individual inputs, outputs and changes in storage (Carter et al., 1979; Winter, 1981). For some reported wetland studies, only one water-budget component is measured or estimated.

Water entering, undergoing temporary storage, and leaving a cypress pond flatwood pine system can be quantitatively expressed in terms of a water budget (Hyatt and Brook, 1984) (Fig. 2.1). The relation of water volume changes in a pond to changes in water budget components for the system per day can be expressed (Heimburg, 1984) as follows:

$$\frac{\Delta V}{\Delta t} = P_P + P_S - ET_P - ET_S + \Delta S_{S/U} + RO \qquad (2.1)$$

where P_p = rate of net rainfall falling on the pond (M^3T^{-1}); P_S=rate of net rainfall falling on the flatwood area (M^3T^{-1}); ET_p= rate of ET losses from the pond (M^3T^{-1}); ET_s = rate of ET losses from the flatwood (M^3T^{-1}); t= time period during which the mass balance was calculated (T); $\Delta S_{s/u}$ = is the variation of combined water storage in groundwater and vadose zone (M^3T^{-1}); RO = rate of surface runoff into (+) or out of (-) the system (M^3T^{-1}); V is the volume of the pond filled with water (M^3). Some of the components of a cypress

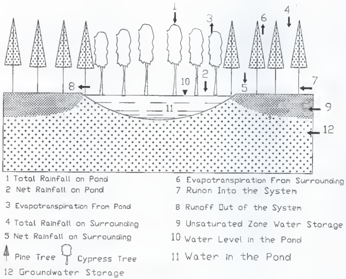
1
3
6
4
8
10
2
5
7
11
9
12
1 Total Rainfall on Pond
2 Net Rainfall on Pond
3 Evapotranspiration From Pond
4 Total Rainfall on Surrounding
5 Net Rainfall on Surrounding
Pine Tree
Cypress Tree
12 Groundwater Storage
6 Evapotranspiration From Surrounding
7 Runon Into the System
8 Runoff Out of the System
9 Unsaturated Zone Water Storage
10 Water Level in the Pond
11 Water in the Pond

Figure 2.1 Hydrological components for cypress pond flatwood pine systems

pond flatwood water budget as measured in the field are summarized in Table 2.1.

Table 2.1. Measured and/or estimated cypress pond flatwood pine water budget components.

	Rainfall (mm)			Evapotranspiration (mm)			Runoff (mm)	
Reference	Total	Net	Interception	Pine	Cypress	Mixed Stand	In	Out
Heimburg (1976)	1070	770	300	n/a	n/a	970	51	0
Nessel & Bayley (1982)	n/a	97.5	n/a	n/a	n/a	64	218	161
Riekerk (1989)	1280	1080	200	n/a	n/a	1110	n/a	12 – 462
Ewel & Smith (1992)	1420	660	n/a	n/a	n/a	n/a	n/a	n/a
Riekerk et al. (1995); Sun, (1995)	1059	900 – 841	158 – 218	795 ± 73	974 ± 61	1021 – 1265	0 – 917	0 – 860

Precipitation (P)

More than half of the average annual rainfall (1370 mm) (Dohrenwend, 1978) in north central Florida occurs during the summer months. Minimal and maximal average monthly rainfall amounts occur during November (44 mm) and in August (208 mm), respectively. Measured long-term average monthly rainfall amounts are presented (Dohrenwend, 1978) in Fig. 2.2. Rainfall in north Florida can be extremely variable

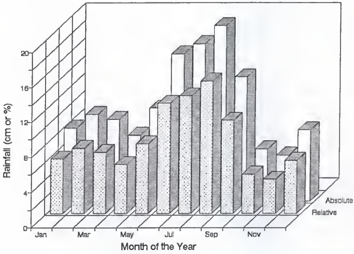

Figure 2.2 Absolute and relative (% annual amount) monthly rainfall for Gainesville, Florida

from year to year, with standard deviations as great as 40% of the mean (Dohrenwend, 1978). Rain accompanying winter frontal storms is usually less intense than that associated with convective (e.g. summer) activity and tends to be more effective for recharge of soil and near-surface storage because surface runoff tends to be minimized.

Total rainfall falling on cypress ponds represents approximately 44% (960 mm) of total water received by the pond (Heimburg, 1976). One quarter of the total rainfall is intercepted by the vegetation and lost to the atmosphere; thus, only 720 mm of the total annual rainfall typically enters the pond as net rainfall.

Precipitation Interception (I)

During the initial stages of interception by a dry canopy, much of the rain water is retained. There appears to be a fairly well defined storage capacity for any given canopy and, when this is exceeded, further intercepted water (net precipitation) either drips from the canopy or runs down the stems. Thus, the difference between gross and net precipitation is designated as "interception loss". Heimburg (1984) reported that interception by pond cypress typically constitutes 25% of total rainfall. This is much higher than the 12% recorded for north Florida slash pine plantations by Voss (1975). In North Carolina, interception was reported to be 13% of the incoming rainfall for a 10-year-old loblolly pine (*Pinus taeda*) stand. The percentage of rainfall intercepted increases with increasing plant ground coverage as measured, for example, by the leaf area index (LAI); thus, the intercepted rainfall by white pine in North Carolina increased to 16% for a 35-year-old stand and to 22% for a 60-year-old stand (Helvey, 1967). Waring et al. (1981) found that interception is generally higher for conifers (e.g. pines) than for deciduous forests, (e.g. cypress). In a recent field study conducted in north central Florida, Riekerk et al. (1995) reported that canopy rainfall interception for an enclosed cypress wetlands was 52 ∓ 11 mm, or 41% higher than for an open pine stand.

Evapotranspiration (ET)

Appreciable transpiration does not occur during winter months for deciduous cypress trees; whereas coniferous pine trees transpire year round. Bushes, vines and other undergrowth species also contribute to ET, however. Transpiration rates for vegetation tend to fluctuate seasonally. Thus, water flow paths in the vicinity of cypress ponds fluctuate in time and space. During wet seasons (June-September) cypress ponds are recharged with direct rainfall and subsurface flow from surrounding pine flatwoods. However, during dry seasons subsurface water moves laterally from the pond to the surrounding pines where a significant but low ET demand remains.

In Florida, ET for slash pine (*Pinus elliottii var.* Engelm.) has been estimated at 100 cm yr^{-1} or 80% of annual rainfall (Riekerk, 1992). Golkin (1981) reported that estimates of transpiration from cuvette-based measurements in a 25-year old pine stand reached 110 cm yr^{-1}. If we add 20 cm yr^{-1} for canopy interception (Riekerk and Korhnak, 1984), total ET amounts to 130 cm yr^{-1}. Using a weighing lysimeter, Riekerk (1985) found the average ET for a young pine tree to equal 108 cm yr^{-1} or 84% of annual rainfall.

Brown (1981) calculated cypress transpiration at 108 cm yr^{-1} using cuvette-based transpiration plus surface water evaporation measurements in cypress wetlands. Canopy interception, which was ≈ 15% of the annual rainfall (Ewel and Smith, 1992), was not considered in these calculations. The average ET of cypress trees with canopy interception included is estimated at 84 cm yr^{-1}, which is less than that of pine flatwoods (Riekerk, 1992). This difference can be attributed to the deciduous and xeromorphic nature of cypress foliage as compared to slash pine needles (Ewel and Smith, 1992). During the summer when the cypress trees have their leaves, ET is approximately 10% less than pan E; in the winter, when cypress trees are without leaves, ET reaches 50% less than PE (Ewel and Smith, 1992).

Riekerk et al. (1995) conducted a cuvette-based ET study of an upland slash pine plantation with embedded pond cypress. They found that annual ET by both forest types ranged from 54 to 95% of annual rainfall and averaged 82 ± 8%. Their data showed little difference in specific transpiration by the two major tree species. Results of a sensitivity analysis conducted recently by Liu (1996) with an average LAI for cypress and slash pine trees predicted no significant difference between ETs from both species. He also predicted a maximum ET of about 1400 and 1200 mm yr^{-1} from cypress wetlands and slash pine uplands, respectively.

Evaporation of Intercepted Rainfall

Coverage of the land surface by vegetation increases surface roughness and enhances eddy transport of heat and water vapor near the surface. Because of this physical effect, evaporation of intercepted rain occurs at rates higher than potential evaporation. Rutter et al. (1975) found that evaporation of water intercepted on the canopies of pine trees was 3 to 5 times greater than the potential transpiration rate; this rate was in the range 0.2 to 0.5 mm h^{-1} even in cloudy weather and in winter.

Runoff

In a full stand for a dry year, the yearly runoff out of a cypress pond is nil; however, the amount of yearly runoff can be as high as 30% of the total precipitation in a wet year (Riekerk, 1989). In north central Florida, average runoff was reported to be 240 mm yr^{-1} for a young pine plantation (Riekerk, 1985). Runoff measured by Tremwel (1992) in Spodosols in the Lake Okeechobee Basin averaged

11-22% of total rainfall. Cypress ponds generally are interconnected during wet seasons across the landscape, though many are formed in isolated sinkhole depressions (Spangler, 1984). The high hydraulic conductivity of surface pine forest soils generates little surface runoff except in saturated zones near cypress wetlands, where runoff pathways may change depending on the degree of flooding (Riekerk, 1992).

Clear-cutting a 40 year-old flatwood forest in north central Florida significantly increased runoff by 150% or 150 mm/yr^{-1} the first year after harvest (Riekerk, 1989); however, this increase had dropped to 65% six years later. Runoff occurrence is related to storm intensity and to depth of the water table. The more intense the storm and the higher the water table, the more likely runoff occurs (Heimburg, 1984).

Dynamic Interaction Between Surface Water in Ponds and Surrounding Groundwater

Three major scenarios have been observed in the field for the dynamic coupling of water flow between cypress ponds and groundwater levels in adjacent uplands. During the first scenario (ground water discharge case) water may flow into ponds from the surrounding area, making the pond a focal point of surface drainage (forward flow) for excess water (Crownover et al., 1995; Sun et al., 1995). In the second case (ground water recharge case), water level in the pond may be higher than the adjacent upland water table;

thus, water may flow away from the pond (reverse flow) to irrigate surrounding forest vegetation (Crownover et al., 1995; Heimburg, 1984). In the last scenario, water may simply flow through the ponds (flow through case) in response to local topographical gradients (Crownover et al., 1995; Heimburg, 1984; Sun et al. 1995). Regional flow may contribute to through flow.

During ground water recharge (reverse flow) conditions, ET provides a dominant driving force for subsurface water flow from the ponds into the subsurface of adjacent pine flatwoods. Since groundwater flow typically changes direction seasonally, solute transport should also follow similar patterns. Thus, the hydrology of pond-flatwood systems greatly influences the potential for chemical contamination of ponds and subsequent drainage runoff between ponds and nearby streams.

Heimburg (1984) reported that surface water levels in cypress ponds tend to fluctuate much less than groundwater levels in adjacent flatwood forests due to the porous nature of the soil. For example, for 1 cm of water consumed from a cypress pond by ET, the pond water level would decrease by 1 cm. However, within soil in a surrounding pine forest the corresponding decrease in groundwater table depth can be much greater than unity because of the finite porosity (example: 0.40 $cm^3 cm^{-3}$) of the soil. Thus, water flow paths in the vicinity of cypress ponds would be expected to be complex in time and space. Even the frequency and spatial/temporal distributions of rainfall must be considered.

Current and Alternative Forest Management Practices

Clear cutting of mature (≈ 20-25 years) pine trees is the conventional method practiced for forest harvest in the southeastern Coastal Plain. Among the controversial aspects of forest clearcutting is the potential for increased water runoff induced by dramatically decreased ET. Nutrient loss, erosion, flooding and subsequent degradation of surface and groundwater quality may result from this sharp decrease in ET (Hornbeck et al., 1975). One alternative to clearcutting is progressive strip cutting, a form of clearcutting that can be carried out in several cycles and over several years. An alternative is to maintain designated buffer zones with unharvested trees in the transitional area between pond wetlands and flatwood forests so as to limit the flow of runoff of water into the ponds. Cypress ponds often can be considered simply as interconnected mini-wetlands that drain coastal plain watersheds to local streams primarily as surface runoff during wet seasons.

Buffer Zones

Buffer strips include vegetated filter strips (VFT), buffer zones (BZ), or filter strips that provide bands of planted or indigenous vegetation. They provide a means to prevent or reduce the transport of sediment (primarily during surface runoff), nutrients, and agrichemicals from land management operations into aquatic environments. Buffer strips are also used to mitigate the potential adverse effects of local agricultural practices upon adjacent surface waters (Comerford et al., 1992).

Buffer zones appear to be generally quite effective in removing soluble nitrogen (N) from water moving through these areas, largely by denitrification but also by absorption by plant roots. More than 80% of NO_3-N is commonly removed (Lowrance et al., 1984; Schipper et al., 1989). Phosphorus (P) removal (uptake by plant roots and sorption onto soil components) is more variable and generally much less efficient than for N, having a range of removal which varies between 0 to 90%. Other major plant nutrients have not received the attention that N and P have, mainly because of a perceived lack of importance in limiting the production of terrestrial or aquatic ecosystems (Comerford et al., 1992).

Best Management Practices (BMPs) in Cypress Pond Flatwood Pine

Because cypress ponds are hydrologically sensitive to forest activities such as harvesting of trees, BMPs are used to regulate timber and pine harvesting activities in these locations. Currently, harvested areas are classified into three main categories (Florida Dep. of Agric. and Consumer Serv., 1991): i) wetland areas less than 80 ha, ii) wetland areas 80 ha and larger; and iii) units which contain five or more small isolated wetlands, each less than 0.8 ha in size. For the latter category, 20% of the number of isolated wetlands must be retained unharvested until the regenerated stands on the other 80% attain an average tree height of at least 6 m (Florida Dep. of Agric. and Consumer Serv., 1991).

Special BMPs have been designated for regulatory areas called Special Management Zones (SMZ). These SMZ areas are specifically associated with identified surface water bodies (lakes, ponds or streams). Such zones are designated and maintained during silviculture operations. The purpose of SMZs is to protect quality of surface water resources by reducing or eliminating forestry-related inputs of sediment, nutrients, logging debris, and chemicals that can adversely affect the aquatic ecosystem. The SMZ has a specific width that is prescribed by the size of the water body, the soil type, and the slope percent.

Evaluating Alternative Management Practices

The impact of intensive forest management practices on water quality and quantity can have both short- and long-term effects. Simultaneously minimizing these detrimental environmental effects on water resources and optimizing forest productivity requires an adequate understanding of the magnitude, timing and duration of hydrological responses to such activities. Conducting field experiments to assess the long-term effects of pine harvest on the hydrology of cypress pond/flatwood areas is costly in time and resources, site-specific, and can only provide answers after long times. Mathematical models offer practical tools for assessing long-term hydrological effects of harvesting (Salama et al., 1993). Modeling endeavors can minimize the number of required field experiments and underscore important parameters and variables that most influence such systems. A modeling approach also offers a means to evaluate the relative importance of hydrological and solute transport processes with advantages of minimizing cost, time, and effort. Once this information is known, future field work can be reduced significantly and realistic quantification of these parameters and overall system response can be estimated.

Recently, Salama et al. (1993) used the numerical model MODFLOW (McDonald and Harbaugh, 1988) to predict the effectiveness of different management options applied to catchments in reducing groundwater discharge and water table rise in low-rainfall saline drylands with hillslopes in Western Australia. Results from their simulations revealed that increasing ET by planting 25% of the catchment with deeply rooted trees should effectively decrease groundwater levels and, consequently, reduce the discharge of saline groundwater at the base of hillslopes. Such predictions agree with previous studies (Bell et al., 1990; Schofield, 1990) for high rainfall areas where 25-50% of reforestation has been shown to be a requirement for the control of groundwater discharge from hillslopes. Location of the trees on hillslopes is also an important factor. Trees planted in recharge areas are well known to reduce recharge into aquifers through increased interception and evapotranspiration, and direct water extraction from the water table provided that plant roots are sufficiently long to reach it.

Modeling the impact of different management practices on the hydrology of cypress pond/flatwood systems requires a multi-dimensional water flow and solute transport numerical model. This model should be able to dynamically link surface water in ponds and underlying groundwaters in surrounding areas. WETLANDS, a modified form of the VS2DT, **V**ariably **S**aturated **T**wo-**D**imensional **T**ransport model, developed by the U.S. Geological Survey (Healy, 1990; Lappala et al., 1987) was utilized for that purpose. Modifications of VS2DT included i) incorporation of a variable-geometry pond with variable water level; ii) incorporation of a sub-model to estimate potential evapotranspiration, using the Priestly-Taylor Equation and a minimum set of daily weather data such as minimum and maximum temperature, latitude and altitude of the location and sunshine ratio; iii) incorporation of the capacity to use different plant root distributions; and iv) incorporation of a dynamic linkage in time between free water in a pond and surrounding water in the porous subsurface (soil water and groundwater) (Bloom et al., 1995). Thus, a multi-dimensional water flow and solute transport modeling effort was undertaken to simulate a dynamic link between one or more surface water bodies to surrounding subsurface (Fares et al., 1993; 1994 and 1995).

Conclusions

A need exists to improve current knowledge of wetland hydrology for cypress pond/pine flatwood ecosystems. The hydrology of cypress pond/flatwood pine ecosystems is dominated by relative flat landscape; hence, evapotranspiration (ET) and rainfall (R) provide the primary hydrological outputs and inputs respectively. The difference R - ET will be used here as net water input. High infiltration rates for water unsaturated sandy soils in flatwood pine forests tend to minimize the generation of surface runoff. Total-harvest scenarios for flatwood pine forests introduce controversial aspects such as increased water runoff induced by decreased ET and elevated groundwater tables. Nutrient loss, erosion, flooding and subsequent degradation of surface and groundwater quality may result from total harvest. Alternative harvesting strategies such as progressive strip cutting and locating unharvested buffer zones in the transitional zone between pond wetlands and flatwood forests have been proposed for controlling water runoff into cypress ponds. Conducting field experiments to assess the long-term effect of pine tree harvesting on the hydrology of the cypress pond flatwood area is costly in time and resources, and is typically site-specific. Numerical hydrological models offer an alternative approach to predict the effectiveness of specific forest management strategies in controlling water table fluctuations and subsequently minimizing chemical contamination of surface water resources. A need exists to utilize a multi-dimensional mathematical model such as WETLANDS for the purpose of investigating hydrological and environmental impacts for the use of unharvested buffer zones in flatwood pine forests surrounding cypress ponds in North Florida.

CHAPTER 3
THEORY OF WATER AND SOLUTE MODELING

A cypress pond flatwood forest system (CPFFS) is a combination of a cypress pond and its surrounding flatwood area (Fig. 2.1). In order to simplify the modeling process of this complex, heterogeneous and dynamic environment three simplifying assumptions were made. The first assumption was that symmetry occurs along a vertical line passing through the center of a circular pond with a maximum radius. The second assumption was that a groundwater divide with zero horizontal water flux was present along a vertical line at the edge of the simulated physical system. The third assumption is that the subsurface hydrologic properties are homogeneous and isotropic within a given soil layer. Thus, effective parameters averaged over the spatial domain of interest must be used in all simulations. In effect, these assumptions reduce the simulation domain to a large circular cross-sectional area over the subsurface flow domain surrounded a smaller circular pond. In other words, regional groundwater flow was neglected. These two assumptions require that only half of the system be simulated (Fig. 3.1). In the model, both surface water in the pond and subsurface groundwater flow are modelled by

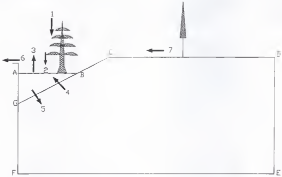

Figure 3.1. A cross-section of the simulated system.

simultaneously solving two coupled equations. The first equation is a mass balance equation based upon all inputs and outputs for water flow into and out of the pond (Fig.3.1). Rates for water volume changes in the pond can be expressed using the water budget as follows:

$$\frac{dV}{dt} = P_p - I_p - E_p + G_i - G_o - SF_o + SF_i \tag{3.1}$$

where P_p (1) = the rainfall rate on the pond (M^3T^{-1}); I_p (1-2) = the rainfall interception rate by the cypress and pine trees in the pond (M^3T^{-1}); E_p (3) = surface water evaporation rate for the pond (M^3T^{-1}); G_i (4) = the subsurface inflow rate for the pond (M^3T^{-1}); G_o (5) = the subsurface outflow rate for the pond (M^3T^{-1}); SF_i (7) = the surface inflow rate for the pond (M^3T^{-1}); SF_o (6) = the surface outflow rate for the pond (M^3T^{-1}); V the volume of the pond (M^3); t the time period when the mass balance is evaluated (T).

Equation (3.1) is coupled with Richards equation for two-dimensional variably-saturated water flow (for homogeneous and isotropic porous media) in the subsurface porous medium surrounding the pond (Eq. 3.2).

$$\frac{\partial\theta}{\partial t} = -\frac{\partial q_x}{\partial x} - \frac{\partial q_z}{\partial z} \pm Q_{water} \tag{3.2}$$

where q_x and q_z are the horizontal and vertical components of water flux, respectively, and Q_{water} is a sink term. Equation (3.2) can be expanded and rewritten as follows:

$$C_w(h)\,\frac{\partial h}{\partial t}=\frac{\partial}{\partial x}\left(K(h)\,\frac{\partial h}{\partial x}\right)+\frac{\partial}{\partial z}\left(K(h)\,\frac{\partial h}{\partial z}\right)-\frac{\partial K(h)}{\partial z}-Q_{water} \qquad (3.3)$$

where the water pressure head $h(x,z) = H(x,z) - z$, $H(x,z)$ [L] is the hydraulic head, z is depth below the soil surface [L], t is time [T], K(h) is the hydraulic conductivity [L T^{-1}] for a given pressure potential (h) value, Q_{water} is a transpiration sink term of dimension [L^3 L^{-3} T^{-1}] or simply [T^{-1}], C_w [L^{-1}] is the specific water storage capacity ($\partial\theta/\partial h = C_w$) for a given value of h.

The sink term, Q_{water}, for water uptake by plant roots in Eq. (3.2) depends upon the soil water pressure potential and was defined by Feddes et al. (1978) as

$$Q_{water}(h) = a(h)\,S_p \qquad (3.4)$$

where the water-stress-response function a(h) is a prescribed dimensionless function (Fig. 3.2) of the soil water pressure head ($0 \le a(h) \le 1$), and S_p is the potential water uptake rate (T^{-1}). The water-stress-response function, a(h), is dependent upon plant type. Water uptake by plants is considered to be zero ($Q_{water} = 0$) when the soil water pressure head is less than or equal to the wilting point pressure head ($h4 = h_{wp} = -15{,}000$ cm of water). As the soil water content increases such that the corresponding pressure head increases above h_{wp}, the water uptake

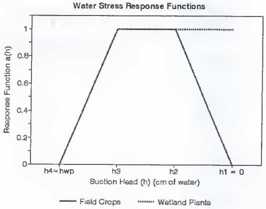

Figure 3.2. The water stress function for field crops and wetland plants.

increases linearly until it reaches an optimal value of S(h) where $h \geq h_3$. The pressure head range $h_{wp} \leq h \leq h_3$ corresponds to a range of volumetric water content $\theta_{wp} \leq \theta(h) \leq \theta_3$ and a range of unsaturated hydraulic conductivity $K(h_{wp}) \leq K(h) \leq K(h_3)$. The water uptake is considered optimal between pressure heads, h_2 and h_3, whereas for heads between h_1 and h_2, for plants that are not adopted to wetland environment, water uptake decreases linearly with increasing h. Water saturation of soil pores occurs at a pressure head h_1 = 0 cm water and water content of θ_{sat}. For most field crops, Q_{water} becomes limiting for water content near θ_{sat} due to the development of anaerobic conditions for plant roots. Pine flatwood and cypress trees are adapted to shallow water table environments, having root systems completely or partially under water during at least part of the growing season. Therefore, water uptake by pine and cypress trees was assumed to continue at optimum rates even under water-saturated conditions.

The potential water uptake rate over a root distribution zone in the subsurface flow domain was defined as:

$$S_p = b(x,z)L_t PT \tag{3.5}$$

where L_t is the width (L) of the soil surface associated with the transpiration process, b(x,z) is the normalized water uptake distribution (L^{-2}), and PT is the potential transpiration rate (LT^{-1}). The normalized water uptake distribution function, also called the root effectiveness function, describes the spatial variation of the potential extraction term, S_p, over the root zone. Nimah and Hanks (1973) linked the root effectiveness function to the weight fraction of the roots in a depth interval relative to the total weight of the roots. The summation of the root effectiveness function over a given soil spatial domain equals unity. Van Rees (1984) found that fifty-nine percent of the total pine root mass was in the upper 40 cm of the soil, while 25% occurred in the 1.4 m thick argilic horizon. Consequently, for simulations reported in this dissertation 60% of pine root water uptake was assumed to occur in the upper 40 cm of soil. Another 25% of water uptake was assumed to result from roots located between soil depths of 40 and 140 cm and the remaining 15% of water was extracted from the 140 cm to the bottom of the soil domain at 250 cm depth.

Plant-root water extraction is determined by both the potential transpiration, PT, and the capacity of the porous media to satisfy this demand. If the soil profile is wet and soil water pressure head occurs within the range $h_3 \leq h \leq h_2$, then the rate of root extraction is equal to the PT. In this case, the transpiration rate, T, is equal to the potential transpiration, PT. However, if water flow in the soil profile can not satisfy the imposed transpiration demand, PT, the transpiration rate, T, will be less than the

PT. Consequently, the actual distribution of water uptake within the soil will be as follows:

$$S(h,x,z) = a(h,x,z)\, b(x,z) L_t PT \qquad (3.6)$$

The potential transpiration used in equations (3.5 & 3.6) is applicable to plants with constant leaf coverage; however, deciduous plants such as cypress trees and annual plants have a variable leaf area index during the year. Consequently, the potential transpiration must be adjusted using a transpiration function (Hanks, 1992; Smajstrla, 1982) to describe the impact of a variable LAI on the PT. More details are given about that transpiration function in the next section.

Estimating Evapotranspiration Using the Priestley-Taylor Approach

Priestley and Taylor (1972) used the following equation to predict an average potential evapotranspiration PET (mm/day) rate:

$$PET = \alpha \, \frac{\frac{\Delta}{\lambda}(R_n - G)}{\Delta + \gamma} \qquad (3.7)$$

where γ (J kg^{-1}) is the psychrometric constant (mb $^{o}K^{-1}$), λ (J m^{-3}) is latent heat of vaporization; Δ (mb $^{o}K^{-1}$) is gradient of the saturation vapor pressure-temperature curve evaluated at the air temperature T_a, R_n (W m^{-2}) is net solar radiation, G (W m^{-2}) is soil heat flux, α is the Priestley and Taylor coefficient, which varies between 1.05-1.38 (Viswanadham et al., 1991). However, Black (1979) recommended using $\alpha = 0.8$. In the case of coniferous forests with no intercepted water, values of α are generally between 0.6 and 1.1 (Spittlehouse and Black, 1981).

The Priestley-Taylor equation is widely used to estimate PET because it is computationally simple and requires measurements of only mean air temperature and solar radiation (Stagnitti et al., 1989). Additional information on how to determine individual components of the Priestley-Taylor equation and consequently, PET are given in detail in Chapter 4. Given the high evaporation rates of the intercepted precipitation on the vegetative canopies of pine and cypress trees, 3 to 5 times greater than the PET rate (Stewart, 1977), the assumption is made that it will not reduce the actual ET from the trees themselves.

The evapotranspiration rate (ET) combines water losses through both evaporation from soil or free water surfaces (E) and transpiration (T) from vegetation. Ground cover greatly influences the magnitude of ET. When plants cover only a small portion of the soil surface, ET is dominated by E. As plant cover increases, evaporation from the soil surface or free water surface (in the pond), decreases and the relative importance of transpiration increases. Several empirical models (Tanner and Jury, 1976; Smajstrla, 1982) related potential transpiration to leaf area development and was computed by multiplying PET with the transpiration coefficient (Hanks, 1985), an empirical function to account for the degree of leaf cover and consequently transpiration variation. This transpiration coefficient should not be confused with the crop coefficient, usually set equal to 0.7, that is used to convert measured pan evaporation from a free surface water into PET (Hanks, 1992).

Recently, Liu (1996) showed that seasonal changes in LAI for pine and cypress trees in CPFS showed different patterns. Mature coniferous pine trees (30 years old) had a LAI that varied around 3.5 (in 1993) throughout the study period. However, deciduous cypress trees, lose their leaves during part of the Fall and all the Winter. Figure 3.3 shows LAI measured by Liu for three cypress ponds in 1993. Thus, a transpiration function identical to cypress trees LAI was used in the WETLANDS model to adjust seasonal variation in cypress PT through the year. In other words, it was assumed that the potential transpiration rates for the cypress trees followed similar patterns as the LAI. The leaf area index for the pine trees was assumed to be constant at 3.5 through the year for a mature pine stand.

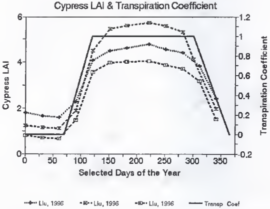

Figure 3.3. Transpiration coefficient for cypress trees.

Potential evaporation. Potential evaporation (PE) from the soil surface can be estimated as a proportion of the total evaporative potential (McCarthy and Skaggs, 1992; McKenna and Nutter, 1984). Developed by Ritchie (1972) and modified by McKenna and Nutter (1984) to apply to forest conditions, the potential evaporation from the soil surface is defined as follows:

$$PE_{soil} = (PET)*Exp(-0.4*LAI) \tag{3.8}$$

Precipitation interception (I). The amount of water present at saturation during rainfall is approximated by a layer of water 0.2 mm thick over the upper surface of the foliage (Rutter, 1975). The saturated interception capacity, I_{sat}, of the canopy is estimated as follows:

$$I_{sat} = 0.2 * LAI \ \ (mm) \tag{3.9}$$

where LAI is the leaf area index of the canopy. Daily interception (I) is calculated using

$$\begin{array}{ll} I = I_{sat} & P => I_{sat} \\ I = P & P < I_{sat} \end{array} \tag{3.10}$$

where I_{sat}(mm) is the saturated interception capacity, P (mm) is the daily precipitation. Interception losses commonly range from 15 to 40% of annual precipitation in coniferous forests and from 10 to 25% in deciduous forests (Rutter, 1975). According to Monteith (1965), Rutter (1967) and Stewart and Thom (1973) the ratio of evaporation rate of intercepted water to transpiration rate is in the order of 4 or 5:1. Especially in forests, there is evidence that evaporation of intercepted water and transpiration occur simultaneously (Van der Ploeg and Benecke, 1981).

Hydraulic conductivity. Hydraulic conductivity for variably-saturated soil has been described as a function of soil water suction head h (or water content θ) using the analytical model of van Genuchten (1980).

$$K = K_s[1+(\alpha*h)^n]^{\frac{-m}{2}}[1-(\alpha*h)^{n-1}(1+(\alpha*h)^n)^{-m}]^2 \qquad (3.11)$$

where K_s is the hydraulic conductivity at water saturation of the soil, $m = 1-1/n$ is a constant, n is a constant, and α is a constant. Values for n, m and α are obtained by fitting the equation

$$S_e = \frac{\theta - \theta_r}{\theta_s - \theta_r} = [1+(\alpha*h)^n]^{-m} \qquad (3.12)$$

to experimental data (θ versus h) from the literature, where S_e is the effective degree of water saturation, θ_r is the residual water content and θ_s is the water content at saturation.

Boundary conditions. The solution of the flow equation (3.2) requires knowledge of the boundary conditions along each side of the 2-dimensional region of interest. The different boundary conditions specified here are described along the simulated system (Fig. 3.1).

The bottom of the system and the two vertical boundaries were prescribed as no-flow boundaries. The upper boundary of the system is a flux boundary that can receive water as rainfall or lose it through evaporation. The boundary conditions for the water flow were, therefore,

$$-K(h)\frac{\partial h}{\partial z} + K(h) = q_0(t,x) \quad for, x \in [C,D] \tag{3.13}$$

$$-K(h)\frac{\partial h}{\partial x} = 0, \quad for\ z \in [D,E],\ [F,A] \tag{3.14}$$

$$-K(h)\frac{\partial h}{\partial z} = 0, \quad for\ x \in [E,F] \tag{3.15}$$

$$-K(h)\frac{\partial h}{\partial x} - K(h)\frac{\partial h}{\partial z} + K(h) = q_{op}(t,x,z)\ for,\ x \in [C,G] \tag{3.16}$$

where $q_0(t,x)$ is the rainfall flux imposed along the soil surface at a given time t, $q_{op}(t,x,z)$ is the flux that is either lost from the subsurface into the pond ($q_{op} < 0$) or entering the subsurface ($q_{op} > 0$) from the pond as pond water or rain falling over the exposed areas of the pond.

Initial conditions. The solution of the Richards' water flow equation requires knowledge of the initial distribution of the pressure head within the flow domain:

$$h(x,z,t) = h_o(x,z) \quad t=0 \tag{3.17}$$

where h_o is the initial pressure head.

Surface runoff. The upper surface of each soil column receives or loses water according to the prevailing rainfall or surface evaporation. Water reaching the soil surface (rainfall) is partitioned into infiltration and excess water. The excess water at the soil surface is handed to next node on the left during the next time step. If excess water occurs, the process is continued for the subsequent nodes, until the excess water reaches the free surface water of the pond. Thus, runoff is approximated as a one-dimensional process directed toward the pond over the upper surfaces of successive soil columns. This is a very simplified implementation of the surface runoff; however, more rigorous approaches are described in the literature.

Solute Transport

Solute transport in this system was simulated using the advective-dispersive solute transport equation (Eq. 3.21) in the subsurface coupled with a solute mass balance equation for the solute present in the pond. The solute mass balance equation for the pond is represented as follows:

$$\frac{dM_p}{dt} = M_{EP} + M_{Gi} - M_{Go} - M_{SFo} + M_{SRi}$$

where M_p = the total solute mass in the pond (M); M_{EP} = the rate for solute mass input into the pond as net precipitation (P-I) over the pond (M T^{-1}); M_{Gi} & M_{Go} = rates for inflow & outflow subsurface solute mass for the pond, respectively ($M\ T^{-1}$); M_{SRi} = the rate for solute mass entering the pond with surface runoff from the flatwood ($M\ T^{-1}$); M_{SFo}= the rate for solute mass leaving the pond with surface flow out of the pond ($M\ T^{-1}$); t = time when the mass balance is evaluated (T).

Convection-Dispersion Transport Equation

The convection-dispersion equation describing solute transport during variably-saturated, transient water flow through a porous medium is developed by a combination of the continuity (conservation of mass) and Darcy's equations and can be written as

$$\frac{\partial}{\partial t}(\theta c) = -\frac{\partial F_x}{\partial x} - \frac{\partial F_z}{\partial z} \pm Q_{solute} \tag{3.19}$$

where θ = volumetric moisture content, dimensionless; c = concentration of chemical constituent, (ML^{-3}); t = time, (T); F_x is the horizontal component for convective-dispersive solute flux, F_z is the vertical component for convective-dispersive solute flux; and Q_{solute} a sourse/sink term,($ML^{-3}T^{-1}$). Expanding equation (3.19) results in

$$\frac{\theta\,\partial c}{\partial t} = \frac{\partial\left(\theta D_h \frac{\partial c}{\partial x}\right)}{\partial x} + \frac{\partial\left(\theta D_h \frac{\partial c}{\partial z}\right)}{\partial z} - q_x\frac{\partial c}{\partial x} - q_z\frac{\partial c}{\partial z} + cQ_{water} \pm Q_{solute} \tag{3.20}$$

Where q_x($L\ T^{-1}$) is the horizontal component for water flux, q_z($L\ T^{-1}$) is the vertical component for water flux. The source/sink terms can be divided into two general categories: solute mass introduced to or removed from the domain by fluid sources and sinks; and mass introduced or removed by chemical reactions occurring within the water and the solid phase (Healy, 1990).

The first category of source/sink terms that have been used in this study can be represented by

$$Q_{solute} = c^{*} q \tag{3.21}$$

where c^{*} = mass concentration in a fluid source/sink, (ML^{-3}); q = strength of fluid source/sink, T^{-1}. If q is positive, the flow is into the system (injection well); however, when q is negative, flow is out of the system (plant uptake). In both cases (into or out of the system), the solute concentration, c^{*}, of the outflow or the inflow should be specified. In the original code of VS2DT, the user can specify only the inflow concentration; however, the concentration of the outflow, c^{*}, was set equal to the ambient solute concentration at the location where flow is leaving the system that is: $c = c^{*}$, (Healy, 1990).

A second category of source/sink terms includes sorption of the solute from the aqueous phase to the solid phase and desorption in the reverse direction. Sorption and desorption processes are physically and chemically driven. If the sorptive process is rapid compared with the rate of water flow, the solute may not come to equilibrium with the sorbed phase, and a kinetic sorption model is need to describe the process (Fetter, 1993). Groundwater movement is usually a slow process; thus, reversible, instantaneous adsorption (equilibrium controlled) is a practical assumption. For all simulations reported in this dissertation, solute in the soil solution and the sorbed phase are assumed to be at equilibrium. The rate of change of solute mass in the sorbed phase is defined as follows:

$$Q_{solute} = \rho_b \frac{\partial S}{\partial c} \frac{\partial c}{\partial t} \tag{3.22}$$

where S is the concentration of solute mass in the solid phase, (MM^{-1}); ρ_b is the soil bulk density, (ML^{-3}). In this dissertation, a linear sorption isotherm equation was used in simulating the sorption of the reactive solute.

The linear sorption isotherm is defined by the relationship as follows (Fetter, 1993):

$$Q_{solute} = \rho_b K_f \frac{\partial c}{\partial t} \tag{3.23}$$

where k_f is the Freundlich adsorption constant.

Boundary Conditions for Solute Transport

The boundary conditions applied to the simulated domain in this study were as follows:

$$-\theta\left(D_x \frac{\partial c}{\partial x}\right) + q_x c = 0, \quad z \in (D, E); (A, F) \tag{3.25}$$

$$-\theta\left(D_z \frac{\partial c}{\partial z}\right) = 0, \quad x \in (E, F) \tag{3.26}$$

$$-\theta\left(D_z\frac{\partial c}{\partial z}\right)+q_o c=q_o c_i, \qquad x\in(C,D) \tag{3.27}$$

$$-\theta\left(D_x\frac{\partial c}{\partial x}+D_z\frac{\partial c}{\partial z}\right)+q_x c+q_z c=q_o^* c_{ip}, \qquad (x\ ,\ z)\in(G,C) \tag{3.28}$$

where c_i is the concentration of the incoming fluid; D_i is the dispersion coefficient in x or z direction, q_o is the incoming water flux, q_0^* can be the incoming flux from the pond or rainfall over the pond in case ($q_0^* > 0$); q_0^* can also be from the subsurface into the pond ($q_o^* < 0$), c_{ip} is the concentration of the incoming fluid ($q_0^* > 0$) or the concentration of the outgoing fluid ($q_0^* < 0$) which is equal to the concentration of the boundary node.

Initial Conditions for Solute Transport

Solving the main solute equation requires specification of the initial conditions for the flow domain:

$$c(x,z,0)=c_o(x,z) \tag{3.29}$$

where c_o is a prescribed function of x and z. c_o can be constant through the system or variable.

Numerical Solutions

Water Flow Equation

The water flow equation is a nonlinear, partial differential equation that has no general closed-form or analytical solution. Thus, numerical approximations to its spatial and temporal derivatives must be made. These approximations result in a set of simultaneous, nonlinear, algebraic equations that must first be linearized and then solved. The spatial derivatives in the flow equation were approximated by a block-centered regular finite-difference scheme. More detailed information about the numerical technique used here is provided by Lappala et al. (1987).

Solute Transport Equation

The parabolic equation for solute transport was solved using a finite-difference approximation. The spatial discretization of the advective component of the solute equation can be either central or backward differencing. The time derivative of the solute equation can be approximated either with a fully implicit (backward-in-time) method or an implicit-explicit, centered-in-time (Crank-Nicholson) approximation. More detailed information about the numerical techniques used can be found in Healy (1990).

Selection of a given approximation method is problem dependent (Healy, 1990). Backward-in-time differencing is first-order accurate in terms of Δt; however, backward-in-space differencing is first-order accurate in terms of Δx. Although the Crank-Nicholson method is more accurate than the fully implicit, it can produce oscillating results around the true solution under certain conditions. Although fully implicit time differencing eliminates such oscillations, it can introduce numerical dispersion or smearing of sharp fronts. Numerical dispersion can be controlled by limiting the size of each time step. In order to insure minimal numerical dispersion relative to physical dispersion, Kipp (1987) recommended enforcement of the following two conditions:

$$\begin{aligned} \frac{\Delta x}{2} &<< \alpha_L \\ \frac{|V|\ \Delta t}{2} &<< \alpha_L \end{aligned} \qquad (3.30)$$

where α_L = longitudinal dispersivity of the porous media, L; $|v|$ = magnitude of the velocity vector, LT^{-1}; x, is the horizontal direction and t is the time.

A disadvantage of the central difference technique is the numerical oscillation. Overshooting and undershooting near sharp concentration fronts for the central difference approximation induce these numerical oscillations. If the following condition is met, numerical oscillation does not occur:

$$\frac{|V|\Delta Y}{|D_{h_{zz}}|} + \frac{|V|\Delta x}{|D_{h_{xx}}|} \leq 2 \qquad (3.31)$$

where D_{hzz} and D_{hxx} are the coefficients of hydrodynamic dispersion in the horizontal and vertical directions, respectively.

In practice, it is difficult to meet this condition and a little more leeway is allowed especially in cases that do not involve sharp concentration fronts (Healy, 1990). In general, the implicit scheme is recommended in most cases. It is essential to remember that numerical solutions are approximations of reality both in time and space; thus, the finer the grid, in space, and the smaller the time step the better the resulting solution. On the other hand, finer grid and smaller time steps may require tremendous computing times.

Model Verification for Water Flow

Validation of the WETLANDS model was performed using field data collected in the flatwoods of north central Florida by other investigators (Riekerk et al., 1992, 1993, 1994; Sun, 1995; Liu, 1996). The research site is located 33 km northeast of Gainesville, FL. Long term studies (monitored since 1991) were conducted for 3 ponds (designated as C, K, N) and their surrounding flatwood pine forest. Two main tree species dominated the system, cypress (Taxodium ascendens) in the wetland along with slash pine (Pinus elliotti) in the pine forest (Sun, 1995). Pond water levels and groundwater table elevations in a flatwood pine forest were recorded continuously with punch-tape recorders. A plot 25 by 25 m was established for each wetland (Liu, 1996) to investigate ET for cypress and pine trees. There was no surface inflow into pond C; however, during wet periods, mainly during winter time (Sun, 1995), surface inflow from adjacent upstream wetlands flowed into K and N ponds. At the same time they were receiving inflow water from one side, the ponds were loosing water as outflow from another side. Thus, the estimated net inflow into these ponds ranged from less than 1% to 4% (Sun, 1995). No recording flumes were installed at the inlets of the K and N ponds, but the surface inflow recording were calibrated by periodic measurements of flow velocity and stage height at the culverts. Elevation data from a 10 by 10 m grid system was used to estimate the volume of each of the three ponds. The annual rainfall of 1512 mm in 1992 was higher than normal, but 1993 and 1994 were dry years with rainfall amounts of only 1137 and 1240 mm, respectively. Detailed information about the study can be found in Riekerk et al. (1993, 1994, 1995); Sun (1995) and Liu (1996). In the spring of 1994, cypress ponds N and K were harvested along with flatwood pine adjacent to N pond. However, pond C and its surrounding remained as an unharvested control.

The hydrology of these three different cypress ponds and their surrounding flatwood area were simulated using WETLANDS model. Most of the input parameters used in these simulations were collected at the research site. Data for soil water characteristic curves of the different soil layers were used from another nearby flatwood site (Philips, 1989). Riekerk et al. (1993) observed that the hydrologic influence of the cypress ponds in question appeared to be about 25 m into the flatwoods landscape. Lateral and vertical groundwater movement in the flatwood forest was limited to areas adjacent to the pond (Sun, 1995). Given these field observations, physical limits of the simulated systems were set to 50 m from the edge of each pond. The radius of each pond was determined based on the estimated pond volumes, surface areas and depths determined by Sun (1995). The validation process included comparing different measured hydrological components to their comparable simulated values for each wetland. Components included, daily pond and ground water table elevations. Measured daily pond water elevations data sets utilized were from 1992 to 1994. However, ground water table data cover the period from April 1993 to December 1994. Transpiration data for the same period (1993-94), measured at the leaf\needle level, for both pine and cypress trees in the three different cypress ponds, N, P and K were used as part of the validation.

Measured ground and pond water elevations were referenced to an arbitrary benchmark level of 30.4 m above the mean sea level(Sun, 1995) for the research site. Average daily water elevations of the three ponds in 1992, 1993 and 1994 were compared to appropriate simulated values in Figures (3.5 - 3.13). Pond water levels were high for all three ponds during most of the 1992 wet year and showed less variability compared to the other two years 1993 and 1994. Lower levels occurred for the different ponds because of low rainfall and high ET demands during the driest part of the year, spring. Simulated and measured pond water levels followed similar patterns. Mean percentage error MPE which quantify differences between measured and simulated data can be calculated in different ways. The obvious way is to used both simulated and measured data based on the bench mark (30.4 m MSL) as reported by Sun, 1995 & Riekerk et al., 1996. However, the MPE can be determined after modifying both measured and simulated data using a new reference level which is the bottom of the simulated physical system. Thus, pond and ground water levels will be reported as elevations above the lower limit of the simulated physical system (2.5 m from the soil surface). Standard deviations (SD) and percentage mean differences between measured and simulated pond water elevations were calculated for each of the three ponds for each of the three years based on the first type of MPE calculation:

$$\textit{Mean Percent Error} = \frac{\textit{Meas. Elev. - Simu. Elev.}}{\textit{Meas. Elev.}} * 100 \qquad (3.31)$$

Values of the MPE and their corresponding standard deviations were less than 1% indicating excellent

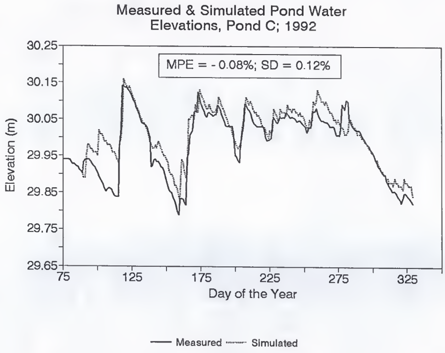

Figure 3.5. Measured and simulated water elevations for the C wetland in 1992.

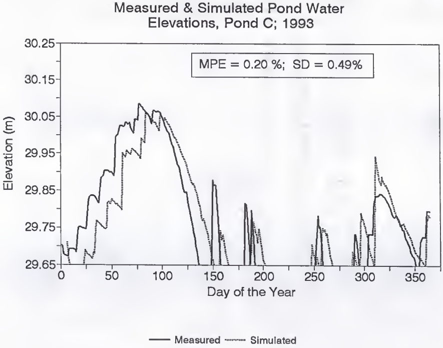

Figure 3.6. Measured and simulated water elevations for the C wetland in 1993.

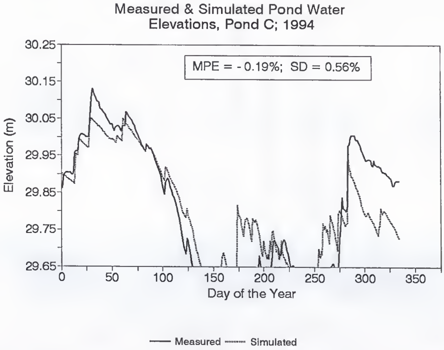

Figure 3.7. Measured and simulated water elevations for the C wetland in 1994.

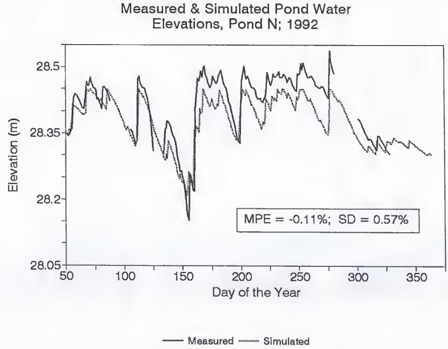

Figure 3.8. Measured and simulated water elevations for the N wetland in 1992.

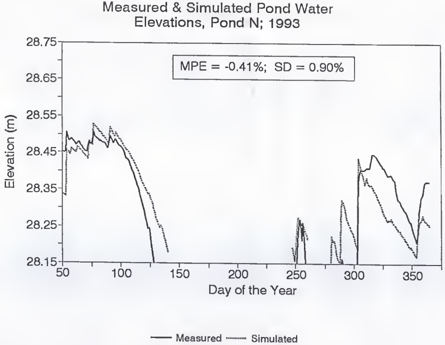

Figure 3.9. Measured and simulated water elevations for the N wetland in 1993.

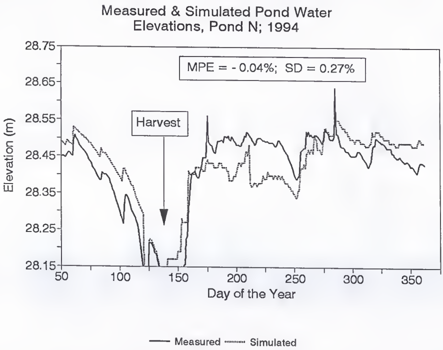

Figure 3.10. Measured and simulated water elevations for the N wetland in 1994.

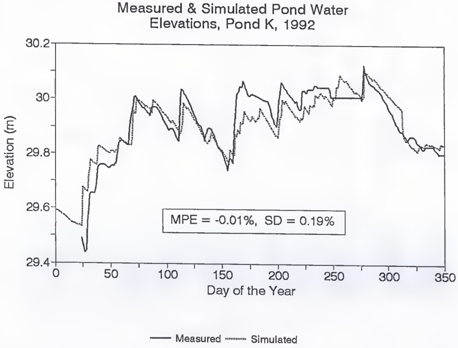

Figure 3.11. Measured and simulated water elevations for the K wetland in 1992.

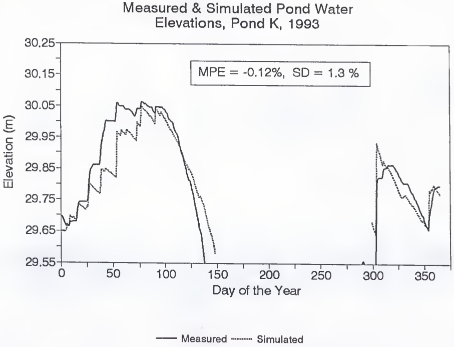

Figure 3.12. Measured and simulated water elevations for the K wetland in 1993.

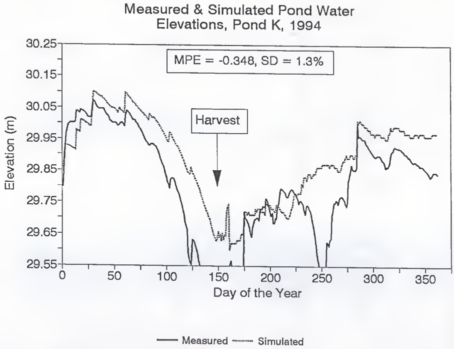

Figure 3.13. Measured and simulated water elevations for the K wetland in 1994.

performance of the model in simulating these CPFS. It is obvious that these low levels of MPE are expected to increase if the second type of MPE calculation was used. Because 1993 was a dry year, all three ponds were dry for a long period of the year, especially during spring and summer seasons. Early spring of 1994 was dry; 1994 was dry; consequently, water levels in the ponds decreased rapidly from high levels during the winter time to a very low level during the end of the month of March. During the months of April and May of 1994, ponds N and K were harvested along with the pine flatwood surrounding pond N; however, pond C and its surrounding were left intact as a control. Consequently, and as a result of combined effects of harvesting and rainfall events, both N and K ponds had higher water levels compared to the control C pond in early June. Even though the simulated values followed the general patterns of the measured pond water levels, differences between simulated and experimental data were encountered. Differences can be partially attributed to the disturbance caused by the harvesting process upon the hydrology of these systems since simulated results for the C pond (control) had less variation from the measured values compared to that for the other two ponds.

The maximum surface area of the wetland in the flatwood system plays an important role in determining the runoff; Riekerk (1992) suggested that the average annual runoff decreased somewhat with an increase of percent cypress wetlands area based on statistical data for 10 flatwood watersheds. The surface area occupied by surface water in the pond varies considerably through the year. Using simulated pond water elevations and pond surface area and volume estimation by Sun(1995), total surface area for water in the N pond was simulated (Fig. 3.14) for wet (1992) and dry (1993) years. During the first 150 days of both years, the two ponds had a very similar variation in surface area. Afterwards, however, two different patterns occurred for the same pond at the end of the winter. In the case of the wet year, the pond surface area was very close to its maximum area for most of the year with relatively small decreases occurring occasionally. During the dry year with a dry summer, the pond was completely dry for more than two months and consequently the pond surface area became zero. In both cases, the end of year was marked by similar surface areas for the pond. It is obvious from the responses of the wet surface of this pond to two different precipitation regimes that the pond size shrinks and expands within the same year and also from year to year due to fluctuations in rainfall and PET imposed on the flatwood system.

Daily ground water elevation in the flatwood forest surrounding the different three ponds are reported in Figures (3.15 - 3.20). Compared to pond water elevations, ground water elevations had more variability in time. One

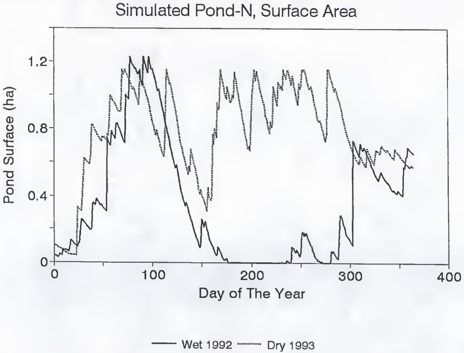

Figure 3.14. Simulated pond surface area for wet and dry years.

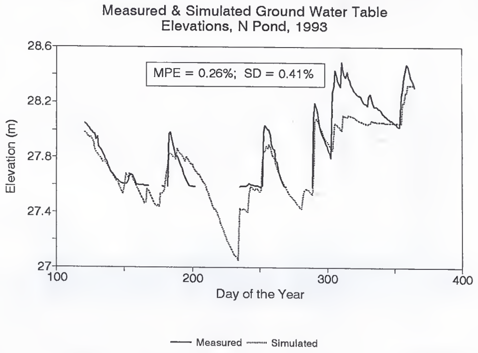

Figure 3.15. Measured and simulated ground water elevations for the N flatwoods in 1993.

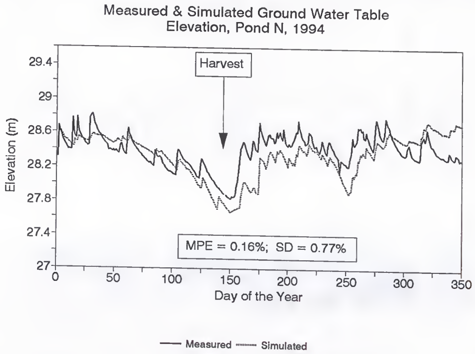

Figure 3.16. Measured and simulated ground water elevations for the N flatwoods in 1994.

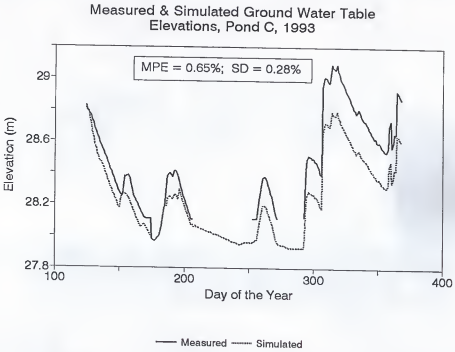

Figure 3.17. Measured and simulated ground water elevations for the C flatwoods in 1993.

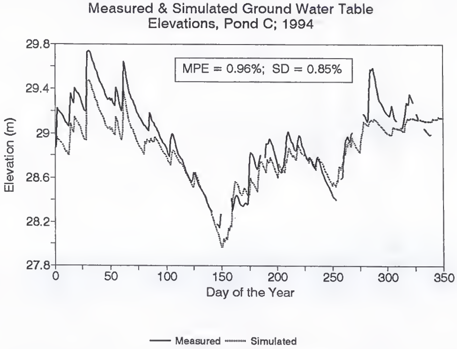

Figure 3.18. Measured and simulated ground water elevations for the C flatwoods in 1994.

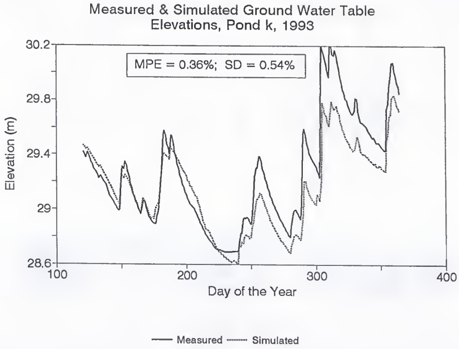

Figure 3.19. Measured and simulated ground water elevations for the K flatwoods in 1993.

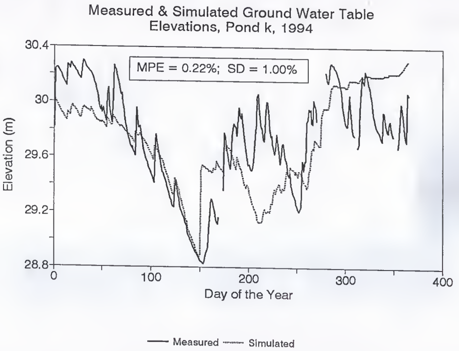

Figure 3.20. Measured and simulated ground water elevations for the K wetland in 1994.

obvious explanation for that variation is the low water storage capacity of the subsurface soil in the flatwood forest compared to the open water surface in the pond. Since a gain or a loss of 1 mm of water in the pond translates in a similar increase of decrease in its water level; however, equal gain or loss from the flatwood of 1 mm would result in a gain or a loss of several mm, 3 to 4 mm, in the ground water table level (Sun, 1995, Heimburg, 1984). The simulated data closely followed the measured data with time. Notice however that the measured rise in water table, especially after heavy precipitation, can be several times higher than simulated groundwater elevation. Many investigators have observed anomalously large rises in water levels in observation wells in shallow unconfined aquifers during and following heavy rainstorms (Sun, 1995; Heliotis and DeWitt, 1987; Freeze and Cherry, 1979). Hooghoudt in 1947 named it the Wieringermeer effect after the Wieringermeer polder in Holland (Heliotis and DeWitt, 1987). Meyboom (1967) reported values of the ratio of water-level rise to rainfall depth as high as 20:1. Several explanations have been given for this phenomenon; however, it is now recognized that this type of water-level fluctuation results from air entrapment in the unsaturated zone (Freeze and Cherry, 1979). After an intense rainfall, an inverted zone of saturation is created at the ground surface, and the rapidly advancing wet front traps air thewater table (Heliotis and DeWitt, 1987; Freeze and Cherry, 1979).

In a field experiment conducted on the same NCASI research site and during the same period (April 1993 to March 1994), transpiration (T) at the leaf/needle level was measured (Liu, 1996; Riekerk et al., 1995b). Liu (1996) used a multi-species and multi-layer ET model, ETME, to scale up transpiration from the leaf/needle micro level to the macro stand level. These data were used here to validate the transpiration generated during the verification of the pond and ground water elevations discussed in the previous section. The transpiration of plant species, used for this validation, in this system have been divided into two components. First, the transpiration of plant species in the pond, mainly the cypress and pine trees (Fig. 3.21-3.23), and secondly, the transpiration of the pine trees in the flatwood forest (Fig. 3.24-3.26).

The upscaled transpiration data for both the pond and the flatwood forest were highly variable compared to the simulated transpiration data using the WETLANDS model. However, the general trends in both data sets was similar. Figure (3.21) shows the simulated and upscaled transpiration data for N pond during 1993. Reasonable agreement occurred between the two data sets, but the best agreement occurred during the first 6 months of the year. Scatter in the upscaled data show values as high as 4 mm of transpiration

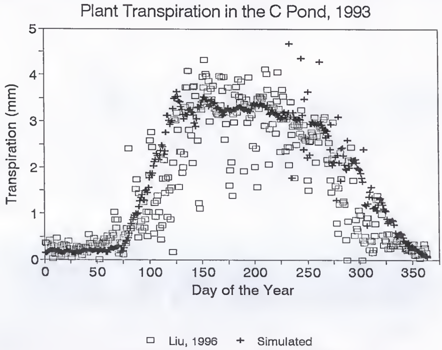

Figure 3.21. Measured and simulated plant transpiration for the wetland C in 1993.

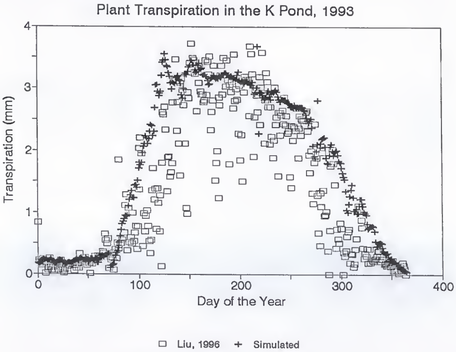

Figure 3.22. Measured and simulated plant transpiration for the wetland K in 1993.

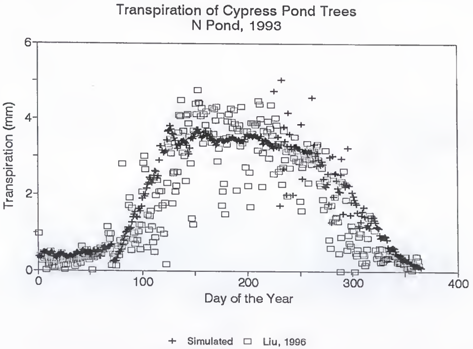

Figure 3.23. Measured and simulated plant transpiration for the wetland N in 1993.

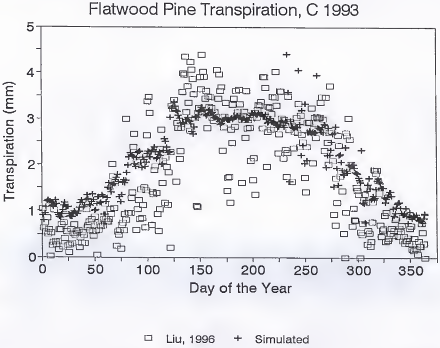

Figure 3.24. Measured and simulated flatwood pine transpiration of wetland C in 1993.

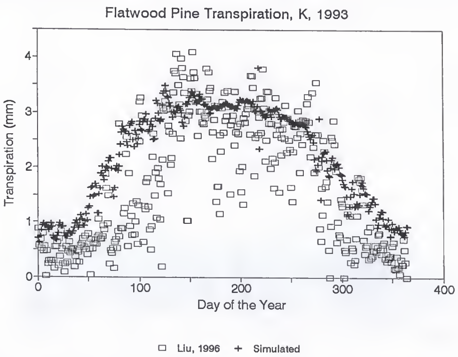

Figure 3.25. Measured and simulated flatwood pine transpiration of wetland K in 1993.

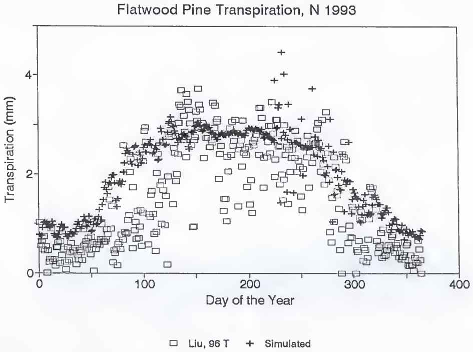

Figure 3.26. Measured and simulated flatwood pine transpiration of wetland N in 1993.

one day and values as low as 1.5 mm on the next day. Simulated T also showed scatter in the data but not as much as in the upscaled T. Because T in the WETLANDS model, is controlled by both imposed PT and the available water stored in the soil, variability was encountered in the simulated T values. Maximum rates of transpiration from the K pond were very similar to those determined by Liu (1996). The highest transpiration rates determined by the WETLANDS model and by Liu (1996) were found during April/May. This same period coincides with that reported in the literature (Ewel and Smith 1992). The maximum rates of transpiration in all three ponds were during the same period and had a very similar magnitude (approximately 3.5 mm/day). These transpiration data sets show a step increase during the period between the calendar days 70 and 120 (Fig. 3.23 - 3.25). During this period, cypress trees typically develop much of their leaves and reach their maximum leaf area index. These results demonstrate the close link between T and LAI.

Flatwood pine transpiration data from the WETLANDS model and Liu (1996) have many similarities to transpiration by pond plants. One obvious similarity is the high variability of the upscaled data (Liu, 1996) data compared to the WETLANDS data. Even though, the maximum T rates for the flatwood pine trees (for both WETLANDS and Liu, 1996) were similar (N and C ponds); these T values were different at the end and at the beginning of the year. During these low transpiration periods, transpiration occurs only from the pine trees since the deciduous cypress trees are dormant. The T data from the pine flatwood trees roughly follow bell shape curves with near symmetry around the middle of the year; however, curves of the cypress have steep slopes at the beginning of the year but have relatively small slopes at the end of the year.

Using some simplifying assumptions and a minimum input data set, the ET submodel linked to the main flow equation in WETLANDS gave realistic transpiration values through different weather patterns and plant species. These validation exercises using real field data demonstrated the capacity of the WETLANDS model to realistically describe the major hydrological behavior of this complex system. The ET submodel successfully provided a realistic approximation of transpiration, a major hydrological component of the cypress pond pine flatwood system. The reasonable simulated results for the main hydrological components of all the tested cypress pond pine flatwoods in north central Florida testify indisputably that the main hydrological components for this system were realistically linked.

Model Verification for Solute Transport

The solute transport portion of the WETLANDS model was verified using two test problems presented here. These two tests were used to verify the mathematical accuracy of the solute transport component of the WETLANDS model. Several analytical solutions for simplified two-dimensional, convective-dispersive solute transport problems are available (Ogata, 1970; Cleary and Ungs, 1978) where steady state unidirectional groundwater flow was assumed to occur a in saturated, homogeneous, isotropic porous medium. For solutes that undergo linear, instantaneous sorption the two-dimensional solute transport equation becomes:

$$D_T \frac{\partial^2 c}{\partial x^2} + D_L \frac{\partial^2 c}{\partial z^2} - \frac{q_z}{\theta}\frac{\partial c}{\partial z} = R\frac{\partial c}{\partial t} \qquad (3.32)$$

where D_L, D_T are the longitudinal and transverse dispersion coefficients, respectively; q_z is the vertical component for water flux in flow direction, $R = 1 + (k_f \rho_b)/\theta$, and z and x are the spatial coordinates parallel and orthogonal to the flow direction. The initially, solute-free water saturated medium is subject to a solute source, c_0, of length 2a at the surface (z=0) where a is a constant. The source is located symmetrically about the coordinate x = 0 (Fig.3.27). Because of symmetry, only half of the system needs to be simulated. The boundary conditions used were:

$$\begin{aligned} &c(x,0,t) = c_o && -a \le x \le a \\ &c(x,0,t) = 0 && \textit{other values of } x \qquad (3.32) \\ &\lim_{(x\to\pm\infty)} \frac{\partial c}{\partial x} = 0; && \lim_{(z\to\infty)} \frac{\partial c}{\partial z} = 0 \end{aligned}$$

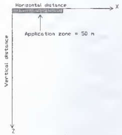

Figure 3.27. Schematic of the physical domain.

An analytical solution for this transport problem was presented by Javandel et al (1984). Transport for reactive and nonreactive solutes were simulated using the WETLANDS model and calculated using the analytical solution. The input parameters for the two cases are listed in the Table 3.1. The width of the source was assumed 100 m and the depth was 100 m. Because of the symmetry, calculations were carried out for only the quarter plane where $x \geq 0$ and $z \geq 0$.

Table 3.1. Input parameters for solute validation.

Parameter	Nonreactive solute	Reactive solute
V(m/day)	0.5	0.5
D_T(m^2/day)	1.0	1.0
D_L(m^2/day)	0.1	0.1
R	1.0	5.0
c_0(kg/m^3)	1.0	1.0

Figure 3.28 shows both the analytical and the numerical solute concentrations throughout the simulated domain at day 365 from the beginning of the calculations for the reactive

solute case. Close agreement occurred between the analytical and numerical results. Similarly, Fig. 3.29 shows the numerical analytical solute concentration through the simulated profile at day 365 for a non-reactive solute based on the input data presented in Table 3.1. Very close agreement occurred between values obtained using the analytical solution and the numerical simulation.

Successful validation of the WETLANDS model enables it to be used as a reasonable tool to assist in solving practical environmental problems. Of particular interest is the impact of forest management practices upon the hydrology and water quality in north Florida cypress pond flatwood pine systems. It is important to mention that more rigorous field data sets are needed for a realistic validation of the solute part of the WETLANDS model. The second main assumption used during model simulations was an assumption of no regional flow. This simplified the simulated system substantially. However, in some practical cases, where regional flow is a major hydrological component of the system, this assumption may be violated. Another assumption assumed a circular pond and a circular cross-section of the simulated system; this simple representation may result in an over simplification of the real system.

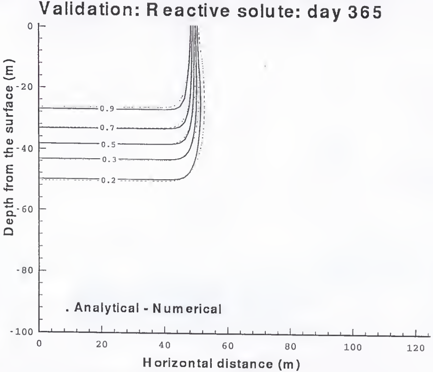

Figure 3.28. Concentration profile for a reactive solute as determined by numerical and analytical solutions.

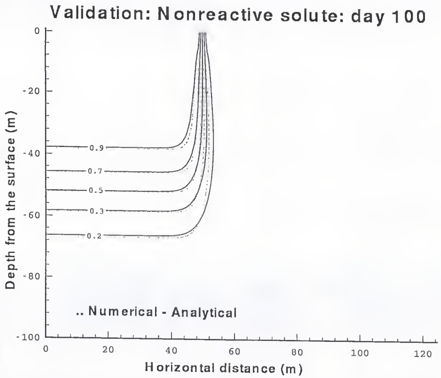

Figure 3.29. Concentration profile for a nonreactive solute as determined by numerical and analytical solutions.

CHAPTER 4

A SUBMODEL FOR PREDICTING POTENTIAL EVAPOTRANSPIRATION FOR MULTI-DIMENSIONAL WATER FLOW IN SOILS

Introduction

Crop growth models and multi-dimensional water flow and solute transport models can be used to optimize existing crop management practices and/or evaluate possible alternative practices in order to both increase crop production and to minimize groundwater and surface water degradation. These models require various combinations of daily or hourly solar radiation (SR), pan evaporation (PE), potential evapotranspiration (PET), and potential transpiration (PET) data. Field measurement of these parameters is usually limited to research contexts, when small areas are subject to intensive study. Collection of such data for long times, and for different locations and environments, can be prohibitive due to excessive costs and labor demands. Reliable mathematical submodels can serve as realistic substitutes for estimating these parameters.

So-called "Weather generators" (Keller, 1987) can be used to estimate SR, PE and PET using available meteorological data as inputs. These generators may provide reasonable data sets for exploring possible modeling scenarios (Hook and McClendon, 1992). The Penman equation

(1948) is the most suitable method for estimating ET from uniform canopies (Dolman, 1988). Using a more stringent analysis, Shuttleworth (1976) developed a multi-layer model to determine ET in forests. However, theoretical advantages of the Shuttleworth model are more than offset by the practical difficulties of developing sufficiently accurate estimates of leaf resistance for all levels of the tree canopy (Stewart, 1984). Thus, in practice the simpler Penman equation and its derivatives, such as the Priestley-Taylor (1972) approach, are advantageous. Despite the empirical nature of the proportionality factor (α), The Priestley-Taylor equation is based upon physical theory and it reduces input data requirements (Buttler and Riha, 1989). It is also a simplified form of the Penman equation and is most reliable in humid climates where the aerodynamic component has been deleted and the energy term multiplied by a constant α (Jensen et al., 1989):

$$\Phi = \alpha \frac{\Delta}{\Delta + \gamma} (R_n - G) \tag{4.1}$$

where $\Phi = \lambda[ET]$ is vapor flux density (MJ m^{-2} t^{-1}), λ is latent heat of vaporization (J kg^{-1}), R_n is net radiation flux (MJ m^{-2} t^{-1}), G is soil heat flux (MJ m^{-2} t^{-1}), γ is a psychometric constant (0.067 kPa $^{o}C^{-1}$), and Δ is the slope of the saturated vapor pressure curve for air (kPa $^{0}C^{-1}$). Evaporation in mm t^{-1} is calculated by dividing λET by the latent heat of vaporization (λ), which has units of MJ kg^{-1}. Alpha (α), an empirical parameter, depends upon the nature of the surface, the air temperature, and time of day (Viswanadham et al., 1991), and soil moisture status (Nemani and Running, 1989). Barton (1979) suggested that α has a value close to unity for forest environments; but, Viswanadham et al. (1991) determined mean values for α of 1.16 (± 0.56) and 1.03 (± 0.13). Priestley and Taylor (1972) obtained a mean α value of 1.26 for an extensive wet surface in the absence of advection. Jury and Tanner (1975) showed that α increases with heat advection from surrounding areas, and suggested a procedure for adapting the Priestley-Taylor equation to such conditions.

The Priestley-Taylor equation (1) requires values for six input parameters: the Priestley-Taylor coefficient (α), slope of the saturation vapor pressure curve for water (Δ), net radiation (R_n), soil heat flux (G), psychrometric constant (γ), and latent heat of vaporization (λ). Figure 4.1 shows schematically how these input parameters are related to equation 4.1.

Objectives for our work were a) to use published equations and a minimum weather data set to estimate input parameters to the Priestley-Taylor equation; and b) use previously calculated parameters for the Priestley-Taylor equation to estimate daily SR, PE and PET. Published daily minimum and maximum air temperature data are generally

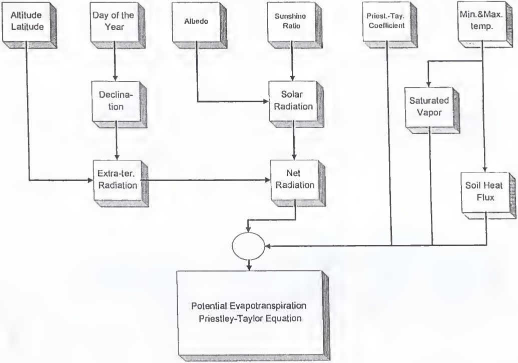

Figure 4.1. Flow chart for the evapotranspiration submodel.

available for most areas of the U.S. or can be obtained from local weather records.

Model Development

A new analytical model to predict potential evapotranspiration in soil-water systems is introduced here. The model is based upon the Priestley-Taylor equation, with daily air minimum and maximum temperatures being used as the main variable input data for a given location.

During the first step of the model procedure (Fig. 4.1), the following input variables are calculated: the saturated air vapor pressure, the heat flux and net radiation, using the day of the year, altitude and latitude of the location, albedo of the surface and minimum and maximum daily temperatures. These calculated variables are then used as inputs for the Priestley-Taylor equation to determine either the PET or the PE, depending upon the value of the albedo (β). In other words, if the albedo is equal to 0.05, the calculated value will be the potential evaporation from a free water surface; however, if the albedo = 0.15 (pine trees), the result will be PET for pine trees. The major steps of our procedure are as follows:

Estimation of Input Parameters for the Model

Daily total values of R_n (MJ m^{-2} d^{-1}) can be determined using several procedures found in the literature. Net radiation, if not measured in the field, can be estimated from daily total incoming solar radiation, R_s (MJ m^{-2} d^{-1}), and outgoing thermal or long-wave radiation. The daily net radiation calculation requires estimation of total incoming solar radiation (R_s), clear sky short wave radiation (R_{so}) and saturation vapor pressure at the dewpoint temperature (minimum temperature is used as the dewpoint temperature). The following relationship was proposed by Penman (1948) and modified by Wright (1982) to estimate net radiation:

$$R_n = (1-\beta)R_s - \sigma\frac{\left(T_{maxk}^4 + T_{mink}^4\right)}{2}(a_1 - 0.139\sqrt{e_d})(a\frac{R_s}{R_{so}} + b) \qquad (4.2)$$

where β is albedo or reflectivity of the surface, σ is the Stephan-Boltzman constant (4.903 x 10^{-9} MJ m^{-2} d^{-1} K^{-4}), T_{maxk} is maximum daily air temperature (°K), T_{mink} is minimum daily air temperature (°K), e_d is saturation vapor pressure at the dewpoint temperature (kPa), and a_1, a, b are empirical coefficients. Accepted values for β are: 0.05 for water surfaces, a range of 0.15 to 0.60 for bare soil surfaces, 0.25 for most agricultural crops, and about 0.10 for forests (Hanks and Ashcroft, 1980). Wright (1982) estimated the a_1 empirical coefficient using

$$a_1 = 0.26 + 0.1\ e^{-[0.0154(J - 180)]^2} \qquad (4.3)$$

where J is the day of the year (1 to 365). For $R_s/R_{so} > 0.7$ (few clouds), a = 1.126 and b = -0.07; for $R_s/R_{so} < 0.7$ (cloudy), a = 1.017 and b = -0.06. The value of a_1

predicted by equation (3) was limited to ≤ 4 during late fall and winter months. Clear-sky short wave radiation. R_{so}, was estimated by Jensen et al. (1989) as

$$R_{so} = 0.75\ R_A \tag{4.4}$$

where R_A is extraterrestrial radiation in MJ m^{-2} d^{-1}. Solar radiation R_s can be measured directly with reliable instruments ranging in complexity from a spring-wound chart and bimetallic sensors to thermopile sensors or silicon cells used in connection with electronic integrators and microprocessor controlled recorders. However, estimates of daily solar radiation also can be made using extraterrestrial radiation, R_A. Doorenbos and Pruitt (1977) recommended the use of a generalized form of the Penman equation to estimate R_s:

$$R_s = (\ 0.25 + 0.5\ \frac{n}{N})\ R_A \tag{4.5}$$

where R_A is the extraterrestrial solar radiation, n is the number of actual bright sunshine hours, and N is the maximum possible sunshine hours for that determinant location.

Values of R_A for various months of the year and latitudes are given in Doorenbos and Pruitt (1977). Monthly and daily values of R_A can also be calculated using the following set of equations developed by Duffied and Beckman (1980):

$$R_A = 37.58 * d_r[\omega_s * Sin(\Phi) * Sin(\delta) + Cos(\iota) * Cos(\delta) * Sin(\omega_s)] \tag{4.6}$$

where R_A is in MJ $m^{-2}d^{-1}$ and ι is latitude of the location in radians (-S,+N). The declination, δ, in radians, can be estimated as

$$\delta = 0.4093\ Sin[2\pi \frac{(284+J)}{365}] \tag{4.7}$$

where J is the day of the year. The term d_r is the relative distance of the earth from the sun, where

$$d_r = 1 + 0.033\ Cos(\frac{2\pi J}{365}) \tag{4.8}$$

The sunset hour angle, ω_s, in radians can be calculated as

$$\omega_s = ArcCos[-Tan(\Phi)\,Tan(\delta)] \tag{4.9}$$

The average daily soil heat flux was approximated by Wright and Jensen (1972) as

$$G = (T_a - T_p)\ c_s \tag{4.10}$$

where T_a is average daily air temperature (^0C) at the z height and T_p is the average daily air temperature (^0C) at that height for the previous 3 days. Parameter c_s is the general heat conductance for the soil surface (Allen et al. 1989).

Saturation vapor pressure (e_d) in kPa at temperature T(^0C) was calculated using the method of Tetens (1930):

$$e_d = \exp\left(\frac{16.78T + 117}{T + 237.3}\right) \tag{4.11}$$

The slope of the saturated vapor function was calculated by taking the derivative of the saturated vapor pressure equation with respect to T:

$$\Delta = \frac{4098\ e_d}{(T + 237.3)^2} \tag{4.12}$$

The psychometric constant, γ, (kPa $^0C^{-1}$) was calculated as follows:

$$\gamma = \frac{c_p P}{\lambda \epsilon} \tag{4.13}$$

where c_p is the specific heat of moist air at constant pressure (1.01×10^{-3} MJ kg^{-1} C^{-1}), P is atmospheric pressure (kPa), ϵ is the ratio of molecular weights of air to water (0.622), and λ is the latent heat of vaporization (MJ kg^{-1}).

Latent heat of vaporization was calculated according to Harrison (1963) as

$$\lambda = 2.5 - (2.361 \times 10^{-3})\ T_a \tag{4.14}$$

where T_a is air temperature (^{0}C). Virtual temperature represents the temperature of a dry air parcel with heat content equivalent to a similar moist parcel.

$$T_v' = \frac{T}{1 - 0.378\ \frac{e_d}{P}} \tag{4.15}$$

where T'_v and T have units of °K, ρ has units of kg m^{-3}, and R is the specific gas constant for dry air (286.9 Jkg^{-1}°K^{-1}).

Based on virtual temperature (T'_v) and the ideal gas law, atmospheric density (ρ) was calculated by Allen et al. (1989) as

$$\rho = \frac{1000\ P}{T_V'\ R} \tag{4.16}$$

The ideal gas law was used by Allen et al. (1989) to estimate mean atmospheric pressure at a given altitude by assuming a constant temperature lapse rate; thus, the resulting equation (Burman et al., 1987) is

$$\Upsilon P = P_0 \left(\frac{T_0 - \Upsilon (z - z_0)}{T_0} \right)^{\left(\frac{g}{\Omega R} \right)} \tag{4.17}$$

where P_0 and T_0 are known atmospheric pressure (kPa) and absolute temperature (°K) at elevation z_o, and P is the desired pressure estimate at elevation z. Parameter Ω is the assumed constant adiabatic lapse rate. Allen et al. (1989) suggested a Υ value of 0.0065 K m^{-1} for saturated air. Gravitational acceleration g equals 9.8 m s^{-2}. Reference values for P_o, T_o, and z_o were set to those for the standard atmosphere at sea level, which are 101.3 kPa, 288 °K, and 0 m, respectively (List, 1984).

Model Validation

Validation of the Net Radiation Component(R_n)

Each of the submodel components was validated using experimental data from the literature. The term $\Delta/(\Delta+\gamma)$from the Priestley-Taylor equation was calculated for different elevations and temperatures and compared with values reported by Jensen et al. (1989). Calculated values were lower than those of Jensen et al. (1989) by only 0.01% to 0.52% (Table 4.1). Such small differences suggest that the submodel provided a good estimate of this term for a wide range of altitudes and latitudes in the northern hemisphere.

Daily extra-terrestrial solar radiation calculated by the model agreed well with values estimated by Jensen et al. (1989) for a location of similar latitude to Gainesville, FL (Fig. 4.2 A). A regression analysis between the data calculated by the model and the data values reported by Jensen et al. (1989) provided a regression coefficient of 0.999. The value of the regression coefficient indicates reasonable agreement between the calculated data and those reported in the literature. According to equation (4.5), daily solar radiation was determined using the predicted extra-terrestrial solar radiation as calculated in the previous step. Clear-sky solar radiation determined for 30^0 latitude also compared well to data published by Budyko (1963) (Fig. 4.2 B). The regression coefficient for comparing the calculated data with the reported data was 0.998. Daily net radiation can be calculated using equation

TABLE 4.1. Simulated and calculated variation of $\Delta/(\Delta + \gamma)$ with elevation and temperature.

A. Values Calculated by Jensen et al. (1989).								B. Values Estimated by the Model						
Elev. °C	0	500	1000	1500	2000	2500	3000	0	500	1000	1500	2000	2500	3000
0	0.403	0.417	0.432	0.446	0.462	0.477	0.49	0.403	0.418	0.433	0.449	0.465	0.48	0.49
5	0.479	0.494	0.509	0.524	0.539	0.554	0.57	0.479	0.495	0.511	0.527	0.543	0.56	0.58
10	0.553	0.567	0.582	0.597	0.611	0.626	0.64	0.553	0.568	0.584	0.599	0.615	0.63	0.65
15	0.621	0.635	0.649	0.663	0.676	0.690	0.70	0.621	0.636	0.651	0.665	0.680	0.69	0.18
20	0.683	0.696	0.708	0.720	0.733	0.745	0.76	0.683	0.696	0.710	0.723	0.736	0.75	0.76
25	0.736	0.748	0.759	0.770	0.780	0.791	0.80	0.736	0.748	0.760	0.772	0.783	0.79	0.81
30	0.782	0.792	0.802	0.811	0.820	0.829	0.83	0.782	0.792	0.803	0.813	0.822	0.83	0.84
35	0.820	0.829	0.837	0.845	0.853	0.860	0.86	0.820	0.829	0.838	0.846	0.854	0.86	0.87
40	0.852	0.859	0.866	0.873	0.879	0.886	0.89	0.852	0.859	0.866	0.873	0.880	0.89	0.89
45	0.877	0.884	0.890	0.895	0.901	0.906	0.91	0.877	0.884	0.890	0.896	0.901	0.91	0.91
50	0.899	0.904	0.909	0.914	0.918	0.923	0.93	0.898	0.904	0.909	0.914	0.918	0.92	0.93
SUM	100	100	100	100	100	100	100	99.99	99.93	99.82	99.72	99.65	99.6	99.5
(Sum A - Sum B)%								0.010	0.070	0.180	0.280	0.353	0.421	0.5

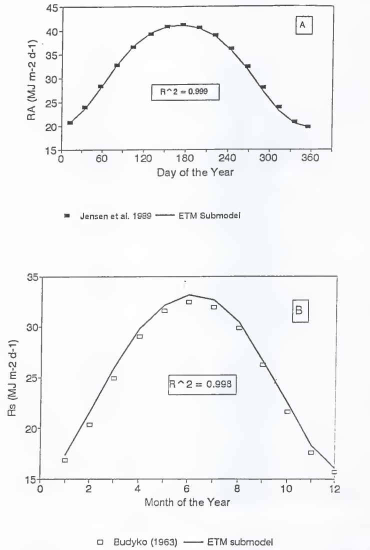

Figure 4.2. Extraterrestrial radiation (A) and cloudless solar radiation (B) for a location at a 30-degrees latitude.

(4.2) by using input values for estimated clear sky solar radiation, minimum and maximum daily temperatures and albedo (reflectivity of the surface).

Prediction of Pan Evaporation (PE)

Daily minimum and maximum temperature data, for Gainesville, FL, (latitude 29.4^{0}N, longitude 82.16^{0}W, and altitude 54 m above sea level), have been recorded for the past 91 years (1903-1994). Daily means and corresponding standard deviations (S.D) were calculated using this data set for minimum and maximum temperatures and pan evaporation (PE). The minimum and maximum temperature data were used in turn to define "cold", "mean", and "hot" weather years (Fig. 4.3), respectively, as follows:

$$\begin{aligned} &\textit{Hot Year}: T_{\min}^{hot} = T_{\min}^{mean} + 1.96*SD;\ T_{\max}^{hot} = T_{\max}^{mean} + 1.96*SD \\ &\textit{Mean Tempearature Year}: T_{\min}^{mean} = T_{\min}^{mean}\ ;\ T_{\max}^{mean} = T_{\max}^{mean} \\ &\textit{Cold Year}: T_{\min}^{cold} = T_{min}^{cold} + 1.96*SD;\ T_{\max}^{cold} = T_{\max}^{mean} + 1.96*SD \end{aligned} \tag{4.18}$$

Temperature data for these three representative types of weather years were used to calculate the corresponding PE. A range of values for α for the Priestley-Taylor equation were used with the "cold", "mean", and "hot" year temperature data to simulate three levels of PE for Gainesville, Florida. Simulated values were compared to experimental daily PE data for the last ten years (1984-

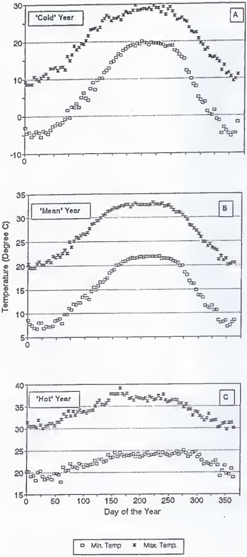

Figure 4.3. Daily minimum and maximum temperature for "Hot", "Mean", and "Cold" years at Gainesville, FL.

1994). A daily measured mean PE and a standard deviation were calculated using the experimental data. Using these two terms, three distinct PE levels were calculated (high, mean and low level) as follows:

$$\begin{aligned} High\ PE &= PE_{avg} + 1*SD \\ Mean\ PE &= PE_{avg} \\ Low\ PE &= PE_{avg} - 1*SD \end{aligned} \tag{4.19}$$

Minimum and maximum temperatures for the previously defined "cold", "mean" and "hot" years were used to simulate three different PE levels. Simulated PE using the "cold" minimum and maximum temperatures were compared to the measured low PE. Similarly, simulated PE using the "mean" and "hot" minimum and maximum temperatures were compared to measured mean PE and high PE, respectively. Different values of the Priestley-Taylor coefficient were used. Coefficient values of 0.8, 0.9 and 1.0 were used in sensitivity analyses for the "cold" year temperature data. Measured and simulated PE for a "mean" weather year are presented in Fig. 4.4. Alpha values of 0.9 and 1.0 were used for the simulated PE. Large variability in the measured PE data made comparison to the simulated data sets difficult. A linear regression analysis was conducted for both simulated data sets with respect to the measured PE data. The results provided that an $R^2 = 0.8$ for both simulations signaling a relatively good fit between

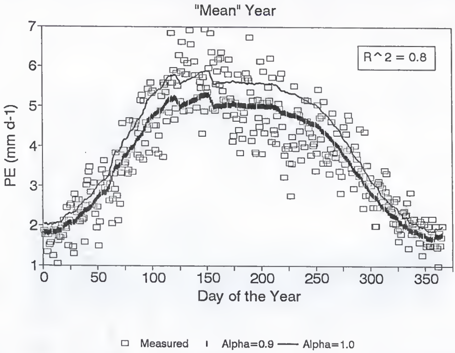

Figure 4.4. Measured mean PE and simulated PE for a "mean" year at Gainesville FL.

simulated and experimental data sets given the high variability inherent in this measured data. Figure 4.5 shows two simulated sets of "hot" weather year potential evaporation data and associated levels of measured PE data. The simulated data using an alpha value of 1.0 and 0.9 track the measured PE data throughout the year better than the other two sets of simulated PE data. Simulated PE with an alpha value of 0.9 under-estimated the measured PE starting at day 125 until the end of the year. A regression analysis between each of the two simulated data sets and the measured high PE resulted in an R^2 value of 0.84. These two simulated data sets provided better description of the corresponding measured PE than those of the "mean" weather year. However, the wide variability in the measured data prevented a better fit of the relatively smooth simulated data sets. In Fig. (4.6), simulated PE are plotted for the "cold" year and associated measured PE. A similar regression coefficient of 0.81 between each of the simulated data sets and the measured PE makes it difficult to determine which simulated PE provided a better description of the measured PE. However, visual inspection indicates that simulated PE with an alpha value of 0.9 is the best fit-candidate for this case.

Prediction of Potential Evapotranspiration (PET)

Figure 4.7 shows total monthly measured (Stewart and Mills, 1965) and simulated PET for turfgrass (Cynodon

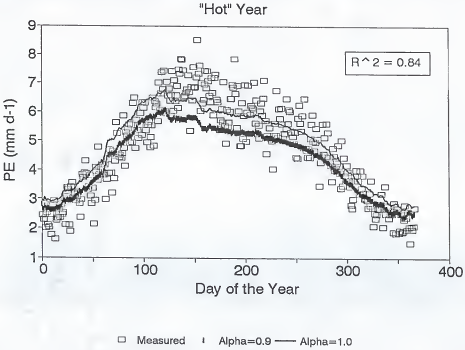

Figure 4.5. Measured high PE and simulated PE for a "hot" year at Gainesville, FL

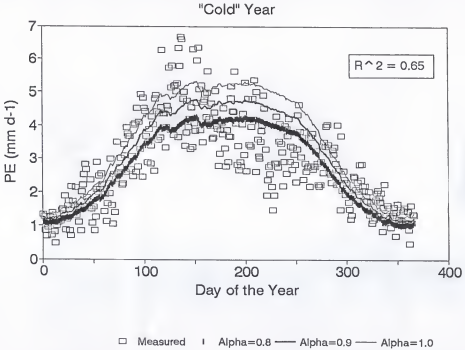

Figure 4.6. Measured mean PE elevations, and simulated PE for a "cold" year at Gainesville, FL.

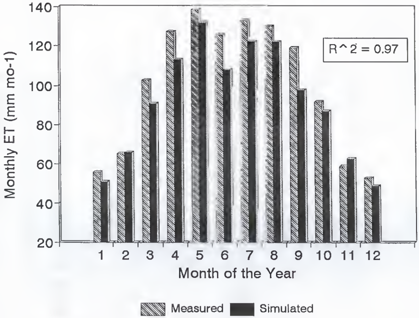

Figure 4.7. Measured ET and simulated PET for turfgrass at Fort Lauderdale, FL

dactylon L.) grown in lysimeters at Fort Lauderdale, FL in 1965 (Stewart and Mills, 1967), with the water table maintained 30 cm below the soil surface. The relatively high water table and high vegetative coverage of the soil surface fits the definition of "a well watered vegetative surface" (Penman, 1956). The submodel was used to simulate daily potential evapotranspiration using minimum and maximum temperature data for that same year and an albedo value of 0.23, corresponding to a grass surface. A regression analysis between the measured and simulated data resulted in a regression coefficient, R^2, of 0.97. This high regression coefficient confirms the similarity between measured and simulated PET. However, simulated ET was slightly higher than measured PET during most of the twelve months. In February, measured and simulated PET were similar; however, during December, measured PET actually was slightly higher than simulated PET. Low measured and simulated monthly PET rates were encountered during the winter months (January-December). High PET occurred during spring and summer months with the highest monthly PET (137 mm) of the year occurring during May. The temporal variation of PET for this turfgrass experiment is similar to that reported for other plant species grown in Florida. The highest measured ET for sugarcane in Florida was 4.9 mm day^{-1} during the month of May (Shih and Gascho, 1980). Ewel and Smith (1992) reported a higher ET value, of 6.8 mm day^{-1} for pond cypress

(Taxodium ascendens Brongn.) trees during April and May. An upper limit of 6 mm day^{-1} has been reported for conifer stands (Whitehead and Jarvis, 1981).

Conclusions

Multi-dimensional water flow and solute models are often used to investigate alternative management practices for plant systems in agriculture and in forestry. Sensitivity analyses are often performed for long simulated periods of time (several years), where input parameters can vary over certain ranges of values. Two of the major input variables to such models are PE and PET. Obtaining long term data for these two components over a wide range of geographic sites is often difficult. Thus, an analytical mathematical model for describing ET and PET was developed for use as a submodel for water flow and solute transport modeling. This submodel uses a minimum weather data set generally available for most locations in the U.S. The data set includes minimum and maximum daily temperatures, latitude and altitude values for the location, the sunshine ratio and reflectivity of the surface. These types of data are readily available and do not require intensive data collection. It is possible, using daily measurements of climatological data from weather stations, to predict PE and PET for different crops. Model predictions of daily extraterrestrial radiation, net radiation, PE, and PET compared favorably to published and measured data.

CHAPTER 5
EFFECTS OF HARVESTING SCENARIOS ON THE HYDROLOGY AND WATER QUALITY OF A CYPRESS-POND FLATWOOD PINE SYSTEM

The WETLANDS model was used to evaluate the relative importance of weather and tree-harvest strategies upon CPFF systems. Tree harvesting was chosen as one of the main variables and five different treatments were included (Fig. 5.1):

I) harvesting scenario # 1 (CONT) = unharvested stand,
ii) harvesting scenario # 2 (PINE) = total harvest (100%) of flatwood pine,
iii) harvesting scenario # 3 (CYPR) = harvest of cypress,
iv) harvesting scenario # 4 (PART) = partial harvest (75%) of the flatwood pine, and
v) harvesting scenario # 5 (TOT) = total harvest of all pine and cypress trees.

Weather was comprised of two variables: precipitation (P) and ambient potential evapotranspiration (PET). Three different levels of P were chosen: high ≡"wet" (1850 mm yr^{-1}), "mean" (1350 mm yr^{-1}), and low ≡ "dry" (850 mm yr^{-1}). Ambient temperature is a major determinant for the PET in the Priestley-Taylor equation. Thus, a high PET level was designated as "hot", average PET as "mean" temperature, and low PET as "cold". The maximum number of possible

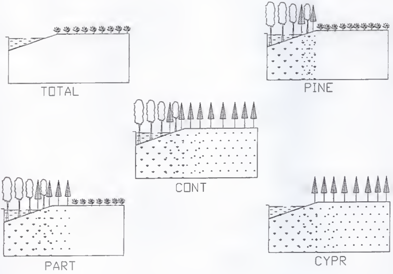

Figure 5.1. Schematics for five different harvesting treatments.

combinations involving the different levels of the input parameters was 45 (3 x 3 x 5 = 45) simulations.

For a given harvesting scenario, there are nine different types of weather years (PET and P varied) as a result of the combination between three levels of each of the PET (C ="cold" (low temperature), M ="mean" (average temperature) and H ="hot" (high temperature)) and the rainfall (W="wet" (high rainfall), M ="mean" (average rainfall), D= "dry" (low rainfall)). Thus, H&D refers to a "hot" and "dry" weather year, M&M to a "mean" PET and P, and C&W is a "cold" and "wet" weather year. A thorough analysis of the simulated results for the nine possible conditions for every harvesting treatment revealed many common similarities for three groups of treatments. Thus, annual simulation results for only three hypothetical weather years: H&D, M&M and C&W were selected for presentation in this chapter. These three weather years encompass the range of PET and P intended for testing.

The simulated CPFF system includes a cypress pond and a surrounding pine flatwood area. The maximum pond size in a typical CPFF has been reported to vary from less than an acre up to several acres (Ewel, 1990). The actual water-filled surface area for individual ponds tends to fluctuate seasonally as rainfall and ET change. Simulated ponds were assumed to have a conical shape with a radius of 50 m and a maximum depth of 0.75 m at the center (≈ 0.8 ha). An overflow outlet was specified at 0.2 m from the soil surface, allowing the water to leave the pond once the water level reaches that limit. Riekerk et al. (1994) reported the hydrological influence of the wetland on the flatwood appeared to be about 25 m into the pine flatwoods; they also added that groundwater fluxes beyond that distance (25m) were significantly lower and are mainly influenced by ET from the flatwood pine forest. Sun (1995) reported that approximately 35% of the Gator National Forest site was in cypress ponds. Based on these two results, the extent of an average flatwood surrounding a circular simulated pond of 50-m maximum radius was chosen to be 75 m of flatwood starting from the edge of the pond. The size of the simulated system was 125 m from the center of the pond to the edge of the flatwood with a subsurface flow domain depth of 2.5 m .

Soils of the cypress pond flatwood pine area are typically Spodosols. Four characteristic soil layers were used beneath the pond and in the flatwood region. The simulated bottom of the pond was covered with a soil layer with 20% organic carbon content. Thickness of each soil layer and its corresponding hydraulic conductivity and soil water characteristic curves were based on field values reported by Philips (1989) on a nearby experimental site (parameter values are given in Appendix A).

The spatial root distribution of pine trees was based upon a field study by Van Rees (1984). Because no documented data in the literature was found for distribution of cypress pond roots, root distribution for cypress trees were assumed to be similar to that for pine trees. In a given vertical soil profile containing plant roots, 66% of the maximum water uptake was delivered from the top 1 m of the soil profile and the remaining 34% was removed from the lower 1.5 m.

Rainfall for an average or "mean" weather year has 1350 mm, 850 mm for a "dry" year and 1850 mm for a "wet" year. The rainfall and temperature data were generated from the weather record of the Agronomy Weather Station at the University of Florida, IFAS. The three PET levels imposed on the system were determined based on the minimum and maximum temperatures of the "hot", "mean" and "cold" hypothetical years determined in Chapter 4. Thus, the potential net water input (NWI = P - PET)for the CONT and for C&W, M&M and H&D weather years were +732, -155, and -766 mm yr^{-1}, respectively. The system layout, a sketch of the physical domain, root distributions for all plant species, rainfall and the remaining input parameters are reported in the appendixes (A).

The spatial descritization of the simulated system was accomplished through a variable grid size for both vertical and horizontal directions (Appendix; Figure A.2). The horizontal grid starts with an initial spacing of 0.05 m for the first two columns of the system, then the spacing for each subsequent column equals the spacing of the previous column times the multiplier, 1.25, until the spacing equals 1.0 m, whereupon spacing becomes constant at 1.0 m. Similarly, the initial spacing in the vertical direction starts at 0.01 m then the spacing for each subsequent row equals a multiplier (1.25) times the spacing of the previous row, until spacing reaches 0.1 m, after which spacing becomes constant to 0.1 m.

All the simulations were run for a year of simulated time. The starting date is January 1st and the ending date is December 31st of the same year. A variable time step was used in the model to increment the simulated time. Minimum and maximum time steps of 10^{-4} and 0.1 day were used, respectively. After conducting a sensitivity analysis, the maximum number of iterations was set to 20 iterations per time step. Upon convergence of the numerical solution, the time step was incremented automatically to the new time step by multiplying the old time step by a factor of 1.25 until it reaches the maximum level. However, if the solution did not converge after two attempts of 20 iterations each, the time step was reduced by a factor of 0.75 until it reached the minimum level. At the beginning of each simulation, the pond and its surrounding subsurface were established at hydrostatic equilibrium; thus, pond water level and ground water in the subsurface were set at 0.65 m from the soil surface.

Two types of output information were generated by the simulation model. The first output type includes daily values of evapotranspiration (ET), water elevation in the pond and the elevation of the ground water table. The second output type for specific report times included surface runoff out of the system, pond and ground water-table elevations from the center of the pond to the end of the system. Spatial and temporal distributions of water pressure or total head, soil solution solute concentration, and water content was also provided throughout the simulated subsurface flow system. Overall water and solute mass balances for the system were reported at every report time. The water and solute mass balance errors ranged between 10^{-4} and 5%. Simulation results were acceptable if their water and solute mass balance did not exceed 5%. Lower time steps and finer grids help lower mass balances errors.

Simulated Evapotranspiration

Annual Evapotranspiration (ET)

During the simulations, PET is imposed over each individual column for the subsurface flow domain in the system as a function of the plant (pine vs. cypress) and surface (soil vs. free water) cover supported by this column. Depending on the availability of the water in soil profile, a portion or all PET is delivered. In other words, the potential ET is delivered if no water stress occurs; otherwise the quantity of water lost as T through plants and evaporation from the soil and/or the water surface E is determined by the amount of water that the soil can supply. Consequently, actual ET is always equal, or less than PET, depending upon availability of water in the system.

Overall effects of the five harvesting scenarios and the three year types upon annual ET were plotted in Fig. (5.2). Annual simulated ET ranged between 660 and 1280 mm. For any harvesting scenario, H&D weather years with high PET and low rainfall had the highest simulated ET level followed by the M&M weather years. As expected, C&W weather year had the lowest ET levels. Total clear-cut treatments where deep-rooted perennial pine trees have been harvested and short-rooted young pine trees with annual plants replaced them, had the lowest yearly ET level within any given year. For each of the 3 weather year, percentage differences between ET for the CONT and the other four harvesting scenarios were determined as follows (Table5.1):

$$\frac{(ET_{CONT} - ET_i)}{ET_{CONT}} * 100 \qquad (5.1)$$

$$where\ i = PINE, CYPR, TOT, or\ PART$$

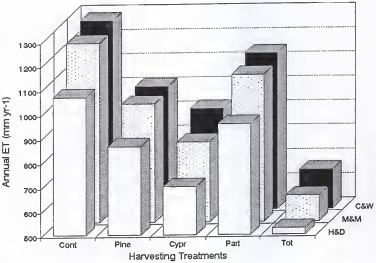

Figure 5.2. Effects of the five harvesting treatments and the three weather years on annual ET.

Table 5.1. Effects of 3 hypothetical weather year and harvesting scenarios on simulated annual ET.

	H&D Weather		M&M Weather		C&W Weather	
Treat.	Amount mm	Change %	Amount mm	Change %	Amount mm	Change %
CONT	1280	0	1251	0	1063	0
PINE	1008	21	988	21	865	19
CYPR	915	29	829	34	700	34
PART	1141	11	1115	11	956	10
TOT	764	40	609	38	656	38

The pine harvest scenario (PINE) had an average of 20% less simulated ET than the unharvested control treatment (CONT). Harvested cypress treatments (CYPR) showed an average 30% ET reduction compared to the control treatments. Total clear-cut (TOT) resulted in a 38-40% decrease in ET when compared to the control treatment (CONT). Note that the partial harvested pine treatments (PART) retained the second highest ET levels after the control since the annual ET was decreased by only 10% of the control.

The simulated annual ET presents the overall behavior of the system. However, daily ET data provide more details important to improve understanding of the hydrology of this CPFF.

Daily Evapotranspiration

Annual distributions for simulated daily ET data were presented separately for the three hypothetical weather years: C&W, M&M, and H&D. Analysis of simulated results were also determined separately for each weather year.

Case#1: Mean PET & P Weather Year (M&M)

Daily ET roughly followed a skewed bell-shaped curve throughout the mean weather year with net water input of -155 mm yr^{-1} (Fig. 5.3). As expected, low levels of ET were simulated for all five treatments during the winter and late fall months. As simulations progressed during the first 120 days of the year, increases in the length of the day and temperature resulted in an increase in the imposed PET on these systems and consequently, daily ET increased almost linearly to reach maximum levels during late April and early May. These maximum ET rates were as high as 5.3 mm d^{-1}. During summer months, the ET decreased slightly and leveled off around 5.0 and 2.75 mm d^{-1} for the control (CONT) and the total clear cut (TOT) treatments, respectively, and remained at those levels during most of the summer. During M&M weather conditions, daily ET values for 100% harvested of the flatwood pines (PINE) were slightly less but with similar patterns to that for unharvested control (CONT). Daily ET values were dramatically less for the total clear cut treatment (TOT) than for the unharvested control. During the first 100 days, ET for the CYPR treatment followed the pattern of the control, but afterward followed the pattern for the TOT treatment. ET was greatly decreased by the harvest of the cypress trees in the pond.

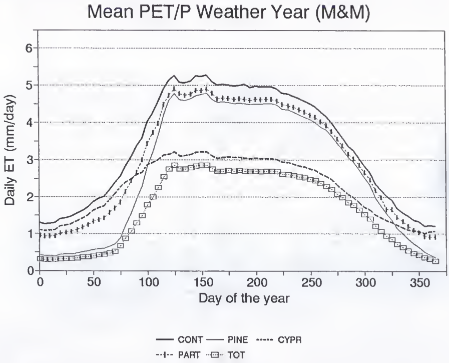

Figure 5.3. Effects of harvesting treatments on ET for mean PET/P year (M&M).

During the first 100 days, ET for the PINE treatment followed the pattern for the TOT treatment, but afterwards it followed the pattern for the unharvested control. It is important to note that all harvesting scenarios decreased ET to some degree relative to the unharvested control, some to lesser extent than others. The maximum ET for the unharvested control exceeded 5.0 mm d^{-1} for M&M weather.

Case#2: The "hot" and "dry" weather year case (H&D)

Simulated daily distributions of evapotranspiration (ET) during extreme "Hot" and "Dry" H&D weather with net water input of -1100 mm yr^{-1} are presented in Fig. 5.4. The highest maximum ET rate for the treatments for H&D weather was 6.1 mm d^{-1} (CONT) which was 14 % higher than the highest maximum rates for harvest scenarios recorded for M&M weather. In the beginning of the simulation, ET rates ranged between 0.5 and 1.9 mm d^{-1} for CONT and TOT treatments, respectively. The range of simulated ET encountered for H&D weather represents an increase of 30 to 65% if compared to the range of comparable harvesting scenarios in the M&M year treatments. Corresponding differences occurred between the rates of ET for the treatments during H&D weather year and during the M&M year. All the harvest treatments, except PART or partial harvest, experienced a severe reduction in ET rates.

Evapotranspiration rates for the control treatment decreased by 45% during the period between days 250 and 270. Spikes

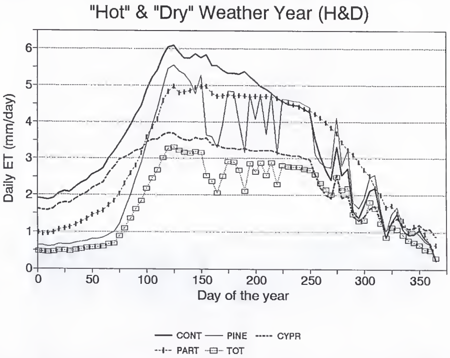

Figure 5.4. Effects of harvesting treatments on ET for a "Hot" & "Dry" weather year

along the ET curves for harvest scenarios during extreme H&D weather are attributed to the high demand upon water stored in the soil and groundwater.

Case#3: The "cold" and "wet" year (C&W)

The ET curves for the harvesting scenarios during the C&W weather with net input of +732 mm yr^{-1} (Fig. 5.5) were similar in pattern but greatly decreased (overall 10-15% reduction) relative to the M&M year treatments. From the first day of the simulated period, ET rates for C&W weather were (0.2 - 0.9 mm d^{-1}) 25-50% lower than comparable rates for M&M weather. This decrease was evident throughout the simulation year and resulted in lower maximum ET rates for all harvesting scenarios. Thus, the highest maximum rate for CONT was 5.3 mm d^{-1} during C&W weather compared to 5.8 mm d^{-1} during M&M weather. However, the lowest maximum rate during C&W weather was 2.65 mm d^{-1} for the total clear cut (TOT) treatment.

Rainfall Interception

Rainfall interception, as it is implemented in the WETLANDS model, is directly related to rainfall intensity and LAI of the stand (equations 3.14 and 3.15); thus, cypress trees, pine trees and the annual plants should have different interception rates given the variability in LAI. Rainfall interception is usually expressed as the total intercepted amount or as a percentage of the incoming

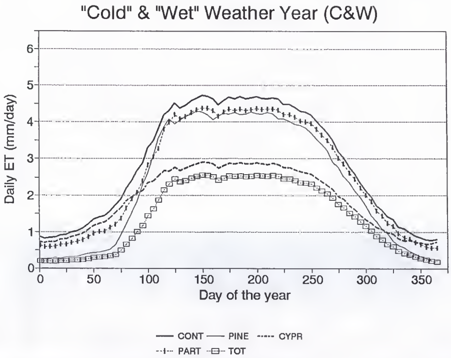

Figure 5.5. Effects of harvesting treatments on ET for a "Cold" & "Wet" weather year

rainfall. Effects of harvesting treatments and rainfall levels on the percentage of rainfall interception have been tabulated in Table 5.2.

Table 5.2. Effect of harvesting scenarios and weather years on canopy rainfall interception.

	CONT		PINE		CYPR		PART		TOT	
Weath. Year	%	Amt mm	%	Amt mm	%	Amt mm	%	Amt mm	%	Amt mm
"Dry" 850mm	28	230	17	140	17	150	20	160	5	40
"Mean" 1350mm	19	250	12	150	11	160	13	180	3	40
"Wet" 1850mm	14	260	9	160	8	160	10	180	2	40

Across the three rainfall years, the total (TOT) clear-cut and unharvested control (CONT) treatments had the lowest and highest percentages of rainfall interception, respectively. The partial harvesting treatments had the second highest interception percentage after the control treatments. The other remaining harvesting scenarios, pine-harvested and pond-harvested treatments, had very similar percentage rainfall interceptions. The percentage of rainfall interception was higher in a dry year than in a mean precipitation year for all 5 harvesting scenarios.

Rainfall interception at the forest stand level is the result of interception by all of the different plant species present in the field. Table 5.3 presents the rainfall interception as a function of the two dominant plant species in the CPFF.

Table 5.3. Rainfall Interception for pine and cypress trees.

	Cypress in Pond		Pines in Flatwood	
Rainfall (mm)	Amount (mm)	Percentage (%)	Amount (mm)	Percentage (%)
850	204	24	180	21
1350	230	18	193	14
1850	240	13	206	11

Regardless of the rainfall level, cypress trees have slightly higher rainfall interception of 3 to 4% than the pine trees.

Surface outflow

Annual cumulative outflow (runoff) from the pond is closely related to the harvesting scenario, amount of precipitation input into the system and to the PET imposed on the system. Any action that reduces the total output from the system or increases the total input, results in an increase in the amount of surface outflow from the system through the pond outlet. Thus, outflow tends to increase with the potential NWI. The impact of different harvesting treatments, temperature and precipitation levels on the yearly outflow and its temporal distribution were investigated. Outflow data is presented for the three hypothetical weather years -C&W, M&M, and H&D- with potential net water input of -766, -155, and +732 mm yr^{-1}.

Table 5.4. Annual outflow as a function of weather and harvesting scenarios.

	CONT		PINE		CYPR		PART		TOT	
Weath. Year	Amt mm	%	Amt mm	%	Amt mm	%	Amt mm	%	Amt mm	%
H&D	0	0	0	0	35	4	0	0	293	34
M&M	0	0	70	6	256	20	41	3	370	29
C&W	532	28	749	40	971	53	677	37	1081	58

Annual outflow ranged from 0 to 58% of incoming rainfall across all harvest and weather years. The unharvested control (CONT) treatments experienced surface outflow only in wet years; however, outflow occurred for the total clear cut (TOT) scenario regardless of the weather year type. The amount and percentage of outflow for the system increased with the increase of the incoming rainfall to the system.

Case#1: Mean PET and P Weather year (M&M)

The highest surface outflow during M&M weather was 370 mm and occurred for the total harvest scenario (TOT). The unharvested scenario treatment (CONT) provided no surface outflow; however, outflow occurred the four remaining harvesting scenarios (Fig. 5.6). Annual outflow was only 41 mm from partial harvest (PART) but the pattern was similar to that for the TOT. The harvested cypress treatment had the second highest cumulative outflow after TOT. Outflow for CYPR and TOT treatments occurred mainly during winter, late summer and fall months. However, outflow for PINE treatments (harvest of flatwood pine trees) took place in just one period of time, between days 90 and 120 of the simulated year.

Case#2: "Cold" and "wet" year (C&W)

The C&W weather year provided considerably more outflow for all harvest scenarios than the M&M weather (Fig 5.7). Outflow occurred from all the harvest treatments during the C&W weather year. The lowest outflow for C&W weather was 532 mm (28%) from the control treatment. Outflow from the partial pine harvest scenario (PART) accounted for 37% (677mm) of the incoming rainfall. A similar percentage of rainfall was lost as outflow (40%) from the pine harvest treatment. More than 50% of rainfall was removed out of the system during C&W weather for TOT (58%) and CYPR (53%) harvest scenarios.

Case#3: Hypothetical "Hot" and "dry" weather year (H&D)

During a H&D hypothetical weather year, outflow occurred primarily for the total clear cut (TOT) harvesting scenario but with only a small quantity from the CYPR

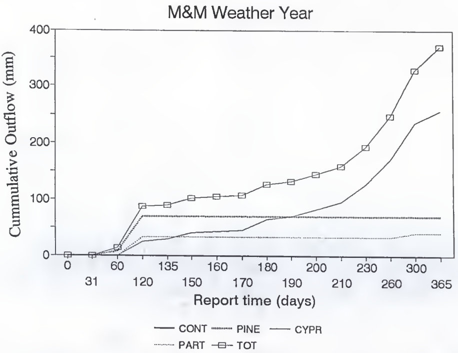

Figure 5.6. Effects of PET and P on cumulative outflow for a mean PET/P year (M&M)

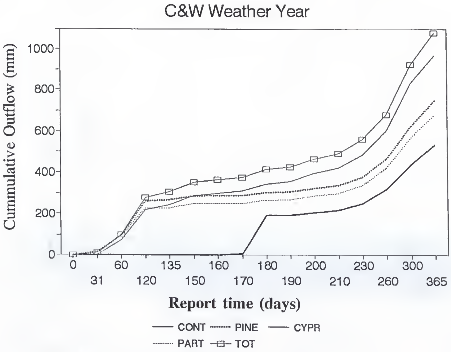

Figure 5.7. Effects of PET and P on cumulative outflow for a "Cold" & "Wet" year (C&W).

scenario (Fig. 5.8). Outflow was not induced for any of the other three harvesting scenarios during H&H weather. Surface outflow for the TOT harvest scenario started at the beginning of summer and increased sharply between days 210 and 260. However, outflow for the CYPR scenario took place mainly during the last 100 days of the simulation. Outflow for the CYPR represents 12% of the outflow amount for the TOT harvesting scenario.

Pond Water Level and Ground Water Table Depth in Flatwood Pine Forest

Daily water level in the middle of the pond and groundwater table level in the flatwood at the outermost edge of the flow system (125 m from the pond center) were reported together with time. Simulated results for these two parameters were reported for five different harvesting scenarios for each of three PET/P cases.

Harvesting Treatment#1 (CONT)

Daily pond water levels for the three hypothetical weather years H&D, M&M and C&W are plotted in Fig. (5.9). Initial water levels in the pond were 65 cm below the soil surface (i.e., the pond bottom). During the first 30 days of the simulated period, water level for ponds increased for all three weather years with time. Pond level continued to increase up until day 80 during the M&M and C&W weather years, but pond levels for the H&D weather year reached maximum by 30 days. For all three weather years, rates of increase were proportional to the rainfall level. Water

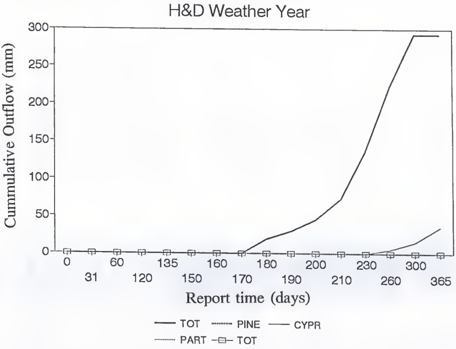

Figure 5.8. Effects of PET and P on cumulative outflow for a "Hot" & "Dry" year.

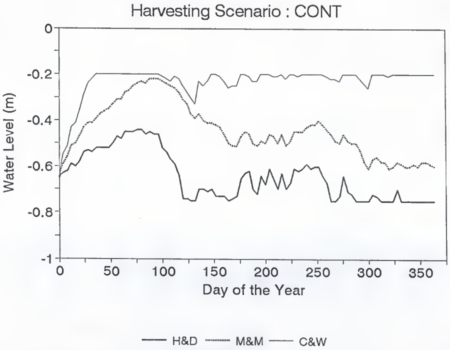

Figure 5.9. Influence of the three hypothetical weather years upon the temporal distribution of daily pond water levels for CONT.

levels in the pond were highest for C&W weather (net water input 732 mm yr^{-1}), lowest for H&D weather (net water input -766 mm yr^{-1}), and intermediate for M&M weather (net water input -155 mm yr^{-1}). During C&W weather, the pond filled to its maximum level quickly and remained so during most of the year with some exceptions during spring (April/May) when PET demand was high and rainfall input was low. During H&D weather years, the pond was actually dry during the last three months of the simulation.

Daily flatwood groundwater table levels in the CONT for the three weather conditions are shown in Fig. 5.10. Initially, simulated water table depth was imposed at the same level as the pond water level. As simulations progressed, three different patterns emerged for the groundwater tables among the treatments. Groundwater tables for C&W weather were very high, within 10 to 15 cm from the soil surface for almost the entire simulation. This result implies that gradients of hydraulic head were such that water flow occurred from the flatwood pine forest into the pond (i.e., groundwater discharge). During M&M weather, a relatively high water table occurred in CONT during the first 100 days of the simulation. Afterwards, groundwater table depth decreased rather dramatically for approximately 50 days, going as low as 1.8 m below the soil surface and remaining there until the end of the simulation. The ground water table depth for the H&D weather year decreased

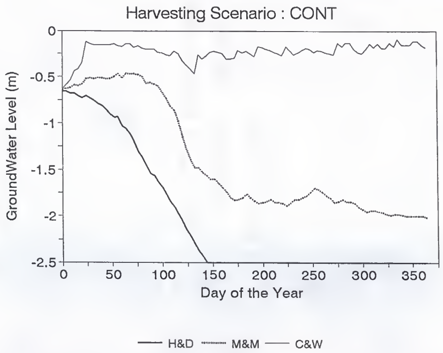

Figure 5.10. Influence of the three hypothetical weather years upon the temporal distribution of daily ground water levels for CONT.

continually for the first 140 days of the simulation. After the end of June, the water table dropped to below the physical bottom (2.5 m) imposed upon the system and remaining there until simulation termination. Depth of the groundwater table in the flatwood showed more fluctuation in time than pond water level, especially during H&D and M&M weather years (Fig. 5.11). During days 100 to 132, ground water levels at the groundwater divide decreased 2.7, 5.0 and 2.1 times that of the decreases in pond water levels for H&D, M&M and C&W weather years, respectively.

Harvesting Scenario #2 (PINE)

Daily pond water levels for the three hypothetical weather years for harvesting scenario #2 (harvest of all flatwood pines) are presented in Fig. 5.12. The behavior of the daily pond water levels for this harvesting scenario was somewhat similar to that for the CONT harvesting scenario. However, the pond water levels were generally higher than those of CONT. During a C&W weather year, the pond was full most of the year with the water level dropping below the maximum pond level only for a few occasions. The largest drop was 10 cm for a few days during June, the driest month of the year. The pond was empty for a number of occasions during the H&D weather year. However, the pond was more than half full during the M&M weather year for more than 65% of the simulation period.

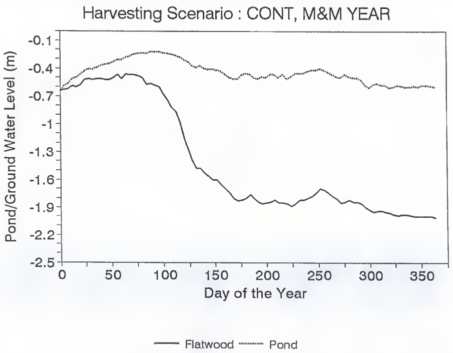

Figure 5.11. Comparison of the influence of the (M&M) mean PET/P weather year upon the temporal distribution of daily pond and ground water levels for CONT.

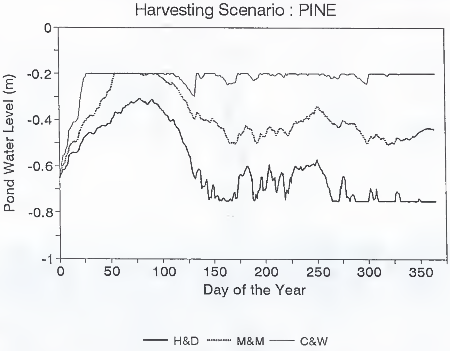

Figure 5.12. Influence of the three hypothetical weather years upon the temporal distribution of daily pond water levels for PINE.

Simulations for all hypothetical weather years rapidly developed high groundwater table levels and continued that way for the first 70 days (Fig. 5.13). Groundwater tables at the edge of the subsurface flow domain were higher than pond water levels during the major part of the first 70 days for both C&W and M&M weather years, but only for a few days during the H&D weather year treatment. As simulations progressed, groundwater tables during the C&W weather year remained very close to the surface and above the pond water level on many occasions. After day 90, groundwater table level for the H&D weather year decreased dramatically over time and continued to drop at a slower rate for the remaining part of the simulation. The groundwater elevation went from being higher than the pond water surface to 1.6 m below the soil surface at the end of simulation.

As expected, both pond water and groundwater table depths for this harvesting scenario (PINE) were higher than those for the CONT scenario for the three weather conditions. On many occasions, the groundwater table level in the flatwoods was higher than the pond water level. As for the CONT scenario, more variability occurred in groundwater level than in pond water level. During a 28-day period from day 120 to 148 for C&W weather, groundwater level dropped 3.1 and 2.3 times more than pond water level for H&D and M&M weather years, respectively.

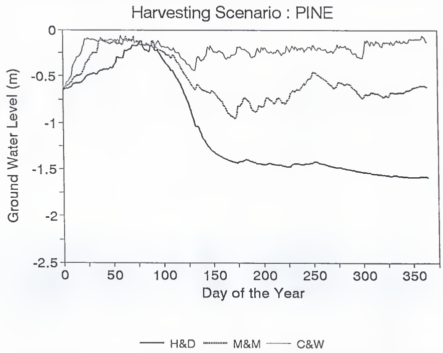

Figure 5.13. Influence of the three hypothetical weather years upon the temporal distribution of daily ground water levels for PINE.

Harvesting Scenario #3 (CYPR)

Cypress tree removal resulted in nearly full ponds for both C&W and M&M weather years (Fig. 5.14). Even the H&D weather year had a full pond during summer months, which was not the case for either the control (CONT) or the harvested pine (PINE) harvesting scenarios. Consequently, outflow for this harvesting scenario was the second highest as compared to total clear-cut.

Groundwater table during the H&D weather year decreased from 65 cm below the soil surface at the beginning of the simulation, to below the flow domain from approximately day 150 to the end of the simulation. During the M&M weather year, a high groundwater table level occurred for the first 100 days and then began decreasing until it reached 1.6 m below the soil surface. It remained at that level during the summer months. At the end of the summer, the water table level increased to approximately 1.2 m below the soil surface and stayed there until the end of the year. During the C&W weather year, the groundwater level was higher than pond water level during most of the year indicating flow into the pond from the pine forest.

Harvesting Scenario #4 (PART)

Pond water levels for partially harvested pine treatments followed similar patterns as the unharvested CONT treatment. The pond was almost full during the entire simulation for the C&W year condition (Fig. 5.15). However,

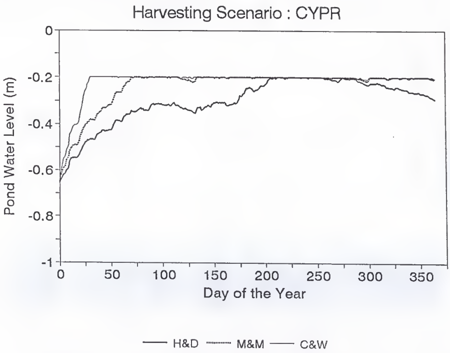

Figure 5.14. Influence of the three hypothetical weather years upon the temporal distribution of daily pond water levels for CYPR.

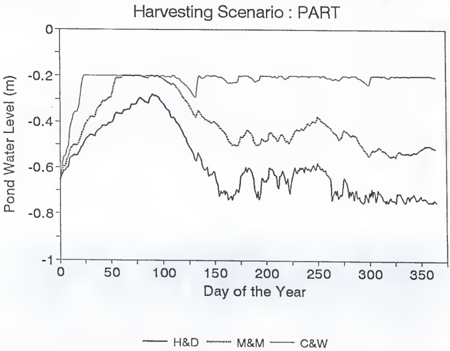

Figure 5.15. Influence of the three hypothetical weather years upon the temporal distribution of daily pond water levels for PART.

during the M&M weather year, the pond was full for nearly a month during the first 100 days and then water level decreased to approximately 45 cm below the soil surface where it varied around that level for the rest of the simulation. After an increase in the first 100 days to an elevation 20 cm below soil surface, the pond water level for the H&D weather year decreased to a lower level for the rest of the simulation. Fluctuations in pond size were evident and the pond was emptied several times during the simulation, especially during the last three months of the simulation. This pattern of the pond water level is similar to the pattern observed for the unharvested control treatments.

Compared to unharvested treatments, groundwater levels for PART treatments were higher (Fig. 5.16). For the Part scenario, the presence of an unharvested buffer (25%) of pine forest surrounding the pond provide a zone of ET which tended to lower the groundwater table in the flatwood region near the pond. Ground water level for the C&W weather year was at a similar level as the pond water level and even higher for several occasions. Groundwater table levels were higher for the H&D, and M&M weather conditions for the first 100 days. After that, ground water levels decreased to a depth of approximately 1.2 m and 1.8 for M&M and H&D weather years, respectively.

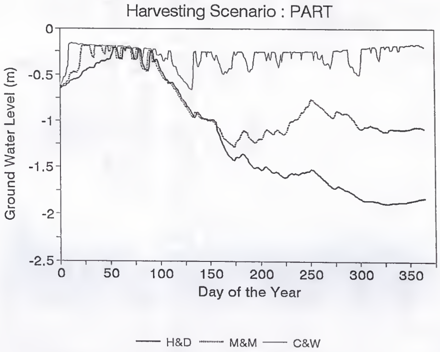

Figure 5.16. Influence of the three hypothetical weather years upon the temporal distribution of daily ground water levels for PART.

Harvesting Scenario #5 (TOT)

Regardless of the harvesting scenario, ponds were full after a period of time of variable magnitude from the beginning of the simulation (Fig. 5.17). The magnitude of this time period was 20, 40 and 160 days for C&W, M&M and H&D year treatments, respectively. At the end of the simulation, pond water level during the H&D weather decreased below the pond bottom of 0.75 m. High pond water levels during most of the year explains the high outflow encountered in each of these treatments.

Groundwater levels were higher for the TOT scenario under all 3 hypothetical weather years than for the other harvesting scenarios (Fig. 5.18). Groundwater table elevations during the three weather years were generally of the order: C&W > M&M > H&D. The deepest level reached during the average M&M year was 70 cm below the soil surface. Groundwater level for the H&D weather year increased during the first 100 days. Afterwards as soon as annual plants were established, groundwater level decreased and eventually leveled off around 1.4 m below the soil surface. It stayed at that level until the end of simulation.

Frequency of Groundwater Table Depth

Wetland hydroperiod as defined by Mitsch and Gosselink (1986), is the duration and frequency of water inundation or flooding during a year. The federal manual for identifying

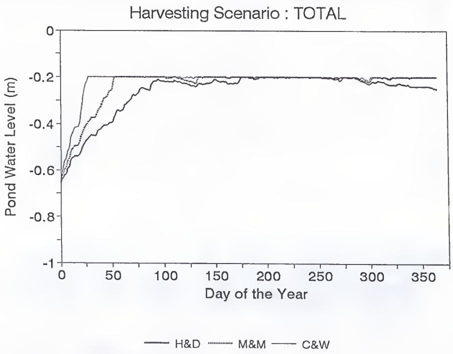

Figure 5.17. Influence of the three hypothetical weather years upon the temporal distribution of daily pond water levels for TOTAL.

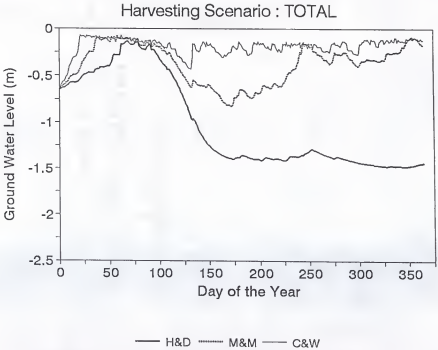

Figure 5.18. Influence of the three hypothetical weather years upon the temporal distribution of daily ground water levels for TOTAL.

and delineating jurisdictional wetlands specifies that if the water table in a given site persists continuously within 15 cm depth of hyperthermic, moderately-drained soils for one week in the growing season the site meets wetland hydrology criteria (US Federal Interagency Committee for Wetland Delineation, 1989). A percentage of frequency was defined as the number of days during one year in which the depth of the groundwater table in the flatwood, at the ground water divide, was less than or equal to 15 cm from the soil surface. Table 5.5 shows the percentage of frequency of the groundwater level in the flatwood for all the three selected treatments.

Table 5.5 Percentage of ground water frequency

Treatments	C&W Year (% Freq.)	M&M Year (% Freq.)	H&D Year (% Freq.)
CONT	05	0	0
PINE	33	13	1
CYPR	16	0	0
PART	13	0	0
TOT	42	18	0

During a C&W weather year, all harvesting scenarios had a frequency percentage at least equal or greater than 5% with TOT treatment having the highest percentage; consequently, all the treatments meet the federal hydrological index of a wetland. However, during a H&D year none of the treatments meet the federal requirements for a wetland. Both PINE and TOT treatments experienced a ground water table level 15 cm or less from the soil surface during a M&M weather year. Frequencies for ground water depths ≤ 15 cm for the PINE and TOT harvesting scenario were 13 and 15% respectively, during a M&M weather year. However, the other three treatments did not experience any ground water table 15 cm or less closer to the soil surface.

The use of an unharvested buffer zone surrounding a cypress pond in the partial harvesting treatment (PART) was thus showed to maintain relatively high ET, very low outflow, a preponderance of water flow away from the pond (groundwater recharge) during much of the year, and relatively deep groundwater to the levels in the flatwood. These results are environmentally and hydrologically beneficial.

Thus, a need exists for detailed investigations of contaminant transport for partial harvesting. Pesticides and fertilizers routinely applied to flatwood pine forests in CPFF systems pose a potential treat to contamination of local cypress ponds and streams. Of particular interest is the impact of the spatial location of the unharvested buffer zone, 25% of the flatwood pine forest, on the spatial responses of pond water, ground water table levels and the solute movement through the simulated domain. The following partial harvest treatments were chosen for this investigation (Fig. 5.20):

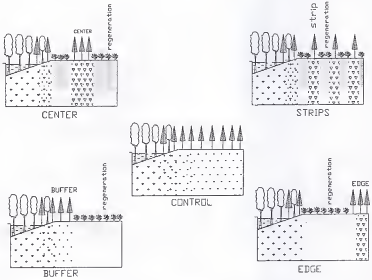

Figure 5.20. Schematics for the different partial harvesting treatments.

I) treatment #1 (CONTROL), The control treatment, an unharvested system with mature trees,

ii) treatment #2 (BUFFER) an unharvested zone (25% of flatwood forest) occurs adjacent to the pond,

iii) treatment #3 (EDGE) the unharvested zone (25% of flatwood forest) occurs at the outside edge or groundwater divide for the flatwood pine forest,

iv) treatment #4 (STRIPS) the unharvested part (25% of flatwood forest) is distributed as three equal strips over the flatwood area,

v) treatment #5 (CENTER) the unharvested part (25% of flatwood forest) occurs midway between the edge of the pond and the ground water divide.

Water flow and solute transport were simulated for a one-year periods for each partial harvest treatment under M&M weather conditions (potential net water input of -290 mm yr^{-1}). The same subsurface flow domain, soil layering, hydraulic conductivities, and soil water characteristics curves, used earlier have been retained in these simulations.

Solute transport simulations included both a reactive (Atrazine, a herbicide) and a non reactive (tracer or NO_3-N) solutes. For the reactive solute, an initial solute concentration equivalent to an application rate of 12.4 kg/ha was uniformly distributed within the soil solution of the upper 10 cm of the upper soil profile over the harvested part of the flatwood (i.e., the outer 75% of the flatwood). In the case of the non-reactive solute, the solute was applied at a rate of 80 kg ha^{-1} over the harvested area (75% of the flatwood pine forest). The solute was applied with incoming rain at a concentration (C_0) of 32.1 g m^{-3} during the first 70 days of the simulation period.

The location of the 25% unharvested buffer zone did not greatly influence either the total water lost from the system as ET or the temporal fluctuation of water level in the pond. Consequently, neither of these components was reported here. Ground water table levels in the flatwood were lower than the pond water level (Fig. 5.21. - 5.25.) for all five reported times (90, 150, 200, 300 and 365 days). Thus, the gradients of hydraulic head were such that the ponds were subirrigating (groundwater recharge) pine trees in the flatwood forest for each of the partial harvest treatments. However, the ground water in the flatwood was high during the winter time and almost at the same level as the pond at day 90. At that simulation time, the pond was full and any excess water was lost as surface outflow to nearby ponds or streams. The water table level was relatively deeper in the immediate vicinity of the unharvested buffer zone due to transpiration by the deep-rooted pine trees. This effect was more obvious during periods of high ET demand (spring and summer) and at a finer

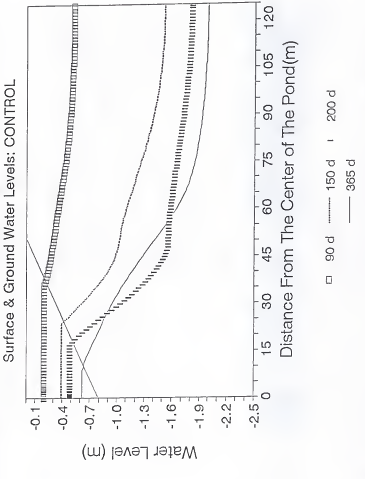

Figure 5.21. Surface and ground water levels for the CONTROL treatment.

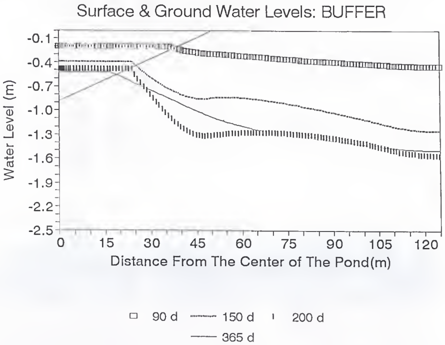

Figure 5.22. Surface and ground water levels for the BUFFER treatment.

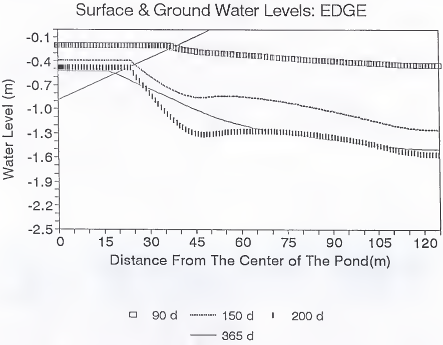

Figure 5.23. Surface and ground water levels for the EDGE treatment.

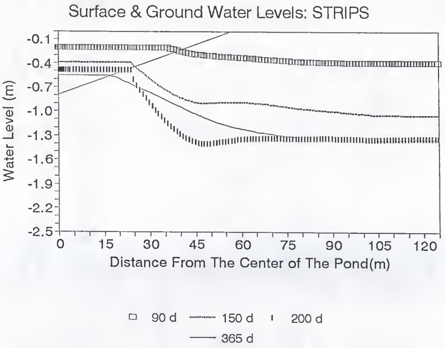

Figure 5.24. Surface and ground water levels for the STRIPS treatment.

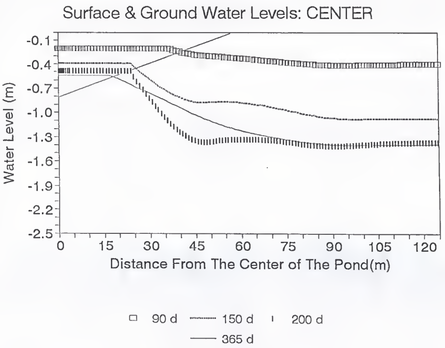

Figure 5.25. Surface and ground water levels for the CENTER treatment.

scale since these depressions in the water table are of the order of a few centimeters.

Effects of Partial Harvesting upon Solute Transport Within Cypress Pond Flatwood Pine Systems

Contaminant transport was simulated for non-reactive (tracer) and reactive (herbicide). Transport of non-reactive solute was simulated with and without uptake by plant roots.

Transport of a Non-Reactive Solute

This non-reactive solute was assumed to be an inert tracer for NO_3-N. The tracer was assumed to undergo no transformation, denitrification or sorption. Simulations were run for the identical system described earlier for water flow. The incoming rainfall had a solute concentration (C_0) of 32.1 g m^{-3} for the same first 70 days of the simulation. Results were presented for each of the five partial-harvest treatments.

Solute transport without plant uptake

Solute concentrations are expressed in g m^{-3}. Table (5.5) shows the solute partitioning over 3 different components at the end of annual simulations for nonreactive solute without plant uptake. These components include solute remaining in the soil, total solute removed through outflow, and the solute remaining in the surface water of the pond. The predominance of the solute remained in the subsurface after 365 days, except the solute portion lost in the surface outflow out of the pond and remaining portion in the pond. These last two solute components are insignificant compared to the solute in the subsurface.

TABLE 5.5. Nonreactive solute, without plant uptake, partitioning throughout the system for a M&M weather year.

Harvest type	Subsurface %	Outflow %	Pond %
CONTROL	100	0	0
BUFFER	99.8	0.1	$< 10^{-6}$
EDGE	99.7	0.2	$< 10^{-6}$
STRIPS	99.7	0.2	$< 10^{-6}$
CENTER	99.7	0.2	$< 10^{-6}$

The part of the solute that enter the pond from the flatwood can come from two different sources: surface outflow and susbsurface water flow. In the first case, solute moves into the pond during periods of high water table when the execess of the incoming water that can not infiltrate into the flatwood ends up into the pond. However, in the second case, solute moves into the pond as a result of the lateral water movement in the subsurface soil from the flatwood toward the pond. To illustrate these two pathways, a one year long simulation for the TOT harvesting scenario was run using a C&W weather year data for a non reactive solute. The same input parameters discussed earlier were used except the rainfall and PET data. The solute reached the pond during the winter time between day

25 and day 75. Sixty one percent of the applied solute ended up into the pond; however, only 85% of this solute that reached the pond was through surface outflow, the remaining 15% did reach via subsurface water flow. It is obvious that the main way that the solute reached the pond was the surface outflow from the surrounding flatwood; however, the solute subsurface transport can not be ignored.

Treatment, #1: CONTROL

The control treatment is the same unharvested treatment used in the water flow simulations discussed earlier. As expected, the lower ground water table level within this system forced the solute to initially move vertically downward in the system to the saturated zone. With increasing time, horizontal movement of the groundwater moved very slowly toward the pond. During the first 60 days, solute movement was mainly downward since the water table was relatively deep; however, as the groundwater table rose closer to the surface and water flow consequently was directed toward the pond, the solute moved laterally toward the pond with a very low concentration of approximately 3% of the initial incoming concentration (Fig. 5.26). This solute movement toward the pond occurred only for a short time since the water table receded during the summer moving the solute plume downward. This plume followed the water table deeper in the subsurface domain and away from the pond. By day 200, the plume had depths from 1 to 1.5 m and

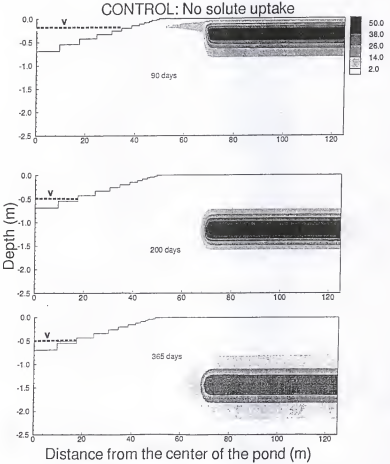

Figure 5.26. Simulated distributions of a nonreactive solute for the CONTROL treatment.

by the end of the simulation, the lower front for the solute plume was beyond 2-m depth. Compared with the other four harvest treatments, the solute plume for the unharvested control treatment spread over a larger area of the flow system. The maximum solute concentration for the control plume was only 50 g m^{-3} (150% of c_o =32.1 g m^{-3}) days 90 and 200. As the contaminant plume moved downward through the root zone, water uptake by plant roots tended to concentrate the contaminant in the soil and groundwater.

On day 90, only slight solute movement was evident at low concentration (2 g.m^{-3}) toward the pond (Fig. 5.26); however, this movement did not continue for a long time. As the ET demand increased, water table receded and consequently, the solute moved down with it.

Partial Harvest Treatment # 2: BUFFER

Movement of the solute plume in the buffer treatment was generally similar to that in the control, but the maximum concentration (92 g m^{-3}) was 1.84 times that in the control (50 g m^{-3}). This higher maximum concentration (270% of C_0 = 32.1 g m^{-3}) was due to the shallow root system (1.0 m depth) in the harvested zone in the buffer treatment compared to a deeper root zone (2.5 m) of the mature pine trees in the control. As the contaminant plume moved downward through the shallow root zone, water uptake by plant roots tended to concentrate the contaminant in the subsurface water. However, after the plume had moved beneath the root zone, the concentration effect no longer occurred. Figure 5.27 shows that by day 90, the solute front for the buffer partial harvest had reached the edge of the pond, but at a low concentration, 2 g m^{-3}. Surface outflow from the flatwood into the pond carried 0.8% of the applied solute into the pond during the simulated period. By the end of the spring and beginning of the summer (day 200), the groundwater table receded and the solute front moved deeper into the soil profile. Lateral solute movement for the buffer treatment spread over a larger portion of the system compared to the control treatment. Low solute (2 g m^{-3}) concentration were left near the pond as the main solute plume moved downward.

Partial Harvest Treatment # 3: EDGE

By day 90 in the EDGE partial harvest treatment, the solute had already reached the pond through both surface and subsurface pathways (Fig. 5.28). The solute concentration that reached the pond was similar to that for the BUFFER treatment (Fig. 5.28). Downward solute movement was spatially variable. The solute moved downward faster in the area of the unharvested pine trees than in the harvested region. The rapidly moving portion of the plume was underneath the unharvested flatwood region of the system and reached 2.0 m depth by the end of the simulation. However, the slowly moving portion of the plume reached 1.5-m depth. Maximum concentrations in both portions of the solute plume

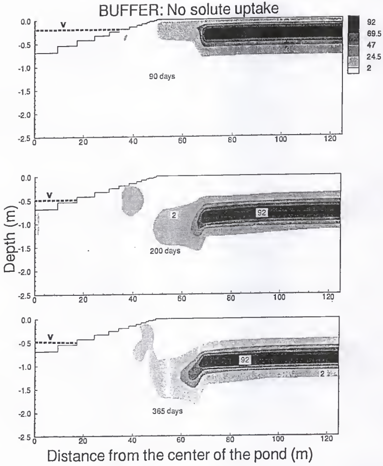

Figure 5.27. Simulated distributions of a nonreactive solute for the BUFFER control.

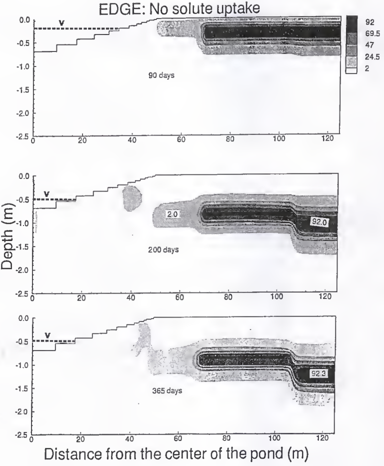

Figure 5.28. Simulated distributions of a nonreactive solute for the EDGE treatment.

were 2.7 times the initial concentration C_0 and 1.8 times that observed in the control treatment.

Partial Harvest Treatment STRIPS #4

For the STRIPS treatment, the nonreactive solute moved partially toward the pond during the first 90 days (Fig. 5.29) due to the gradients of hydraulic head which resulted in water flow from the flatwood toward the pond (i.e., ground water discharge). Solute was carried downward faster through the unharvested strip areas due to water uptake from the deep roots of the unharvested pine trees. The contours for solute concentration reflect a strong influence of the root zone location. Later during the simulation period, solute began moving downward in the area close to the pond. At the end of the simulation, the solute plume had reached deeper than 2.0 m below the soil surface. For the strips treatment, solute was spread over larger and deeper areas than in the previous treatments. Consequently, higher solute concentrations in the plume at 365 days were approximately only 56.1 $g.m^{-3}$ (175% of the initial concentration c_0).

Partial Harvest Treatment #5 CENTER

The solute plume was observed to move faster downward in the region underneath the unharvested pine trees with deep roots than in the harvested regions on either side with shallow root systems (Fig. 5.30). For the CENTER treatment, the solute moved laterally toward the pond as in the

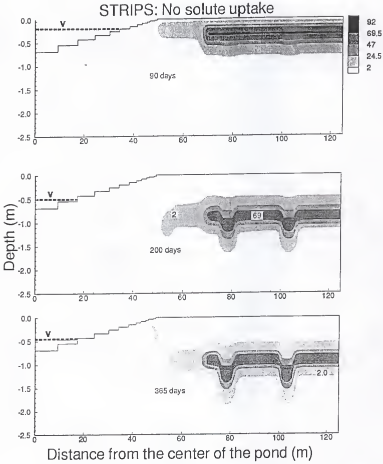

Figure 5.29. Simulated distributions of a nonreactive solute for the STRIPS treatment.

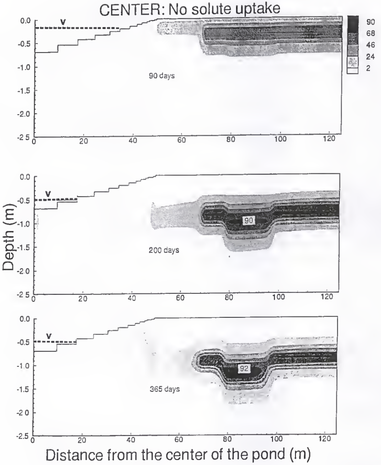

Figure 5.30. Simulated distributions of a nonreactive solute for the CENTER treatment.

previous treatments. In this case, a very low concentration was shown to link the solute in the area under the pond to the main subsurface solute plume. The highest solute concentration at the end of the simulation (92 g m^{-3}) was 2.9 times the initial concentration of the incoming solute.

Transport of Nonreactive Solute With Plant Uptake

Solute uptake during solute transport was assumed to occur at one half of the ambient concentration in the soil solution. Table (5.6) shows the solute partitioning over 4 different components at the end of annual simulations. These components include total plant uptake, solute remaining in the soil, total solute removed through outflow, and the solute remaining in the surface water of the pond. The plants absorbed from 71% to 76% of the amount that entered the system. The remaining 23 to 28% of the solute was left mainly in the mobile soil solution of which less than 1% was lost in the surface outflow through the pond.

TABLE 5.6. Solute partitioning in a M&M weather year.

Treatments	Uptake (%)	Soil (%)	Outflow (%)	Pond (%)
CONTROL	71	28	0	0
BUFFER	76	21	< 1	$< 10^{-6}$
EDGE	75	23	< 1	$< 10^{-6}$
STRIPS	75	23	< 1	$< 10^{-6}$
CENTER	75	23	< 1	$< 10^{-6}$

The general behavior of the solute movement for each treatment was similar to behavior by the non-absorbed tracer In addition to the use of a medium rainfall level, a high rainfall level (wet year:1850 mm rainfall) was used to investigate the fate of the non-reactive tracer. Solute partitioning into the different components of the system at the end of a 1-year simulations was shown in Table 5.7. except that much lower concentrations were observed in the subsurface solute plumes. The treatments of this case are characterized by two main characteristics. First, less of the solute spreading plumes occurred in the subsurface system as compared to similar treatments in the case without solute uptake by plant roots. Secondly, the maximum solute concentrations in the soil solutions were several times lower than the initial input concentration (C_0) into the system. During the first ninety days of the simulations for all the five treatments, the solute spreading with plant uptake was very similar to the spreading without plant uptake (Fig. 5.31 - 5.35). However, maximum solute concentrations in solute plumes were similar to the concentration of the incoming rainfall (32.1 g m^{-3}) during the first 70 days of the simulations.

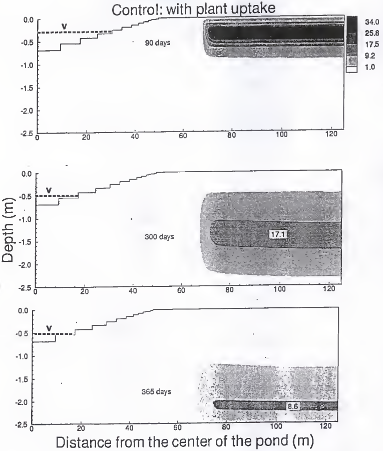

Figure 5.31. Simulated distributions of a nonreactive solute with uptake for the CONTROL treatment.

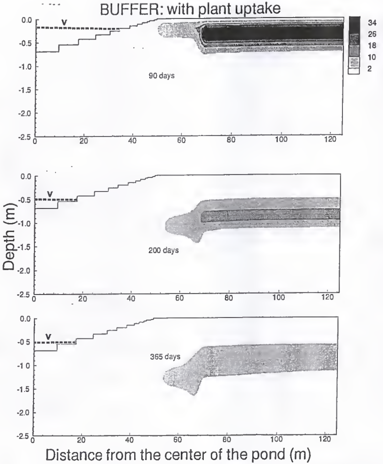

Figure 5.32. Simulated distributions of a nonreactive solute with uptake for the BUFFER treatment.

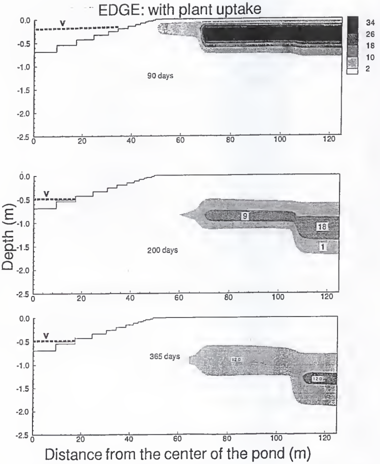

Figure 5.33. Simulated distributions of a nonreactive solute with uptake for the EDGE treatment.

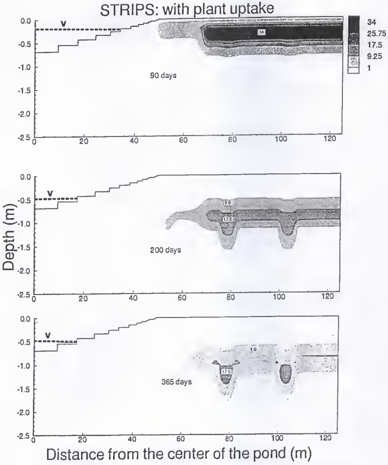

Figure 5.34. Simulated distributions of a nonreactive solute with uptake for the STRIPS treatment.

Table 5.7. Partitioning of nonreactive solute, with plant uptake, throughout the system for a wet year.

Treatments	Uptake (%)	Soil (%)	Outflow (%)	Pond (%)
CONTROL	52	29	13	$< 10^{-6}$
BUFFER	54	27	15	$< 10^{-6}$
EDGE	53	26	15	$< 10^{-6}$
STRIPS	53	28	15	$< 10^{-6}$
CENTER	60	26	13	$< 10^{-6}$

Regardless of the partial harvesting treatment, 13-15% of the solute input into the system flowed into the pond surface water under high rainfall conditions, compared to < 1% for medium rainfall conditions. Thus high rates of solute were lost from the system with the outflow water in the system. Plant uptake ranged from 52 to 60% of the total solute input for a wet year as compared to a range of 71 to 76% for mean rainfall year.

Transport of Reactive Solute: A Herbicide

Solute transport simulations for a reactive (Atrazine, a herbicide) solute were used to predict the fate of such pollutant in the CPFS. An initial solute quantity equivalent to an application rate of 12.4 kg/ha (with the incoming rainfall of the first day of the simulation), recommended for weed control in forest, was uniformly applied over the harvested part of the flatwood (the outer 75% of the flatwood) at the beginning of the simulation. The partitioning of the reactive solute between the soil solution and the adsorption site is mainly proportional to the percentage of organic carbon present in soil (Rao et al. 1983). The partition coefficient for the reactive solute (Fetter, 1992) was determined as follows:

$$K_d = K_{oc}\, OC \tag{5.2}$$

where: k_d is the partition coefficient; it defines the ratio of pesticide concentration in the adsorbed-state and the solution-phase; K_{oc} is the partition coefficient of the reactive solute with respect to the organic carbon fraction present in the soil; OC is the mass fraction of organic fraction present in the soil. A K_{oc} value of 100 (Nkedi-Kizza et al.; 1985) was used for Atrazine. The top soil layer of the flatwood, used in previous non-reactive solute simulations, was divided into two different soil layers with different organic carbon content. The new top soil layer has a higher organic carbon (4%) as compared to the second soil layer that only has (1%) of organic carbon content. The sorption coefficients and organic carbon contents for each of the soil layers used were reported in appendix A.

The general shape for the plumes of concentrations of the reactive solute in the subsurface aqueous phase for the CONTROL and BUFFER partial harvest treatments was similar (Fig. 5.36 - 5.37). Plumes for This solute moved very slowly downward and laterally through the soil profiles as compared to the plumes for the nonreactive solute. The maximum solute concentration in soil solution was below 2 mg l^{-1} early in the simulations (90 days); however, as solute spread over the subsurface domain, its maximum concentration in the soil solution decreased to approximately 1.5 mg l^{-1} by day 200 and even to lower values by the end of the simulation. As expected, the solute plume for the unharvested CONTROL treatment moved deeper in the profile than the plume for the BUFFER partial harvest.

As seen for the nonreactive solute case, the solute plume in the unharvested pine flatwood area for the CENTER partial harvest flatwood moved deeper than the plume in the harvested area of the flatwood forest. Thus, solute at 0.1 mg l^{-1} concentration reached 1.0 m of depth from the soil surface (Fig. 5.38) at the end of the simulation (day 365) in the unharvested part for the CENTER partial harvest. However, in the harvested part of the flatwood, the solute plume only reached 0.65 m deep in the soil profile. The reactive solute plume for the STRIPS partial harvest showed some similarities with the plume for the nonreactive solute (Fig. 5.39). The strip areas were the subject of deeper

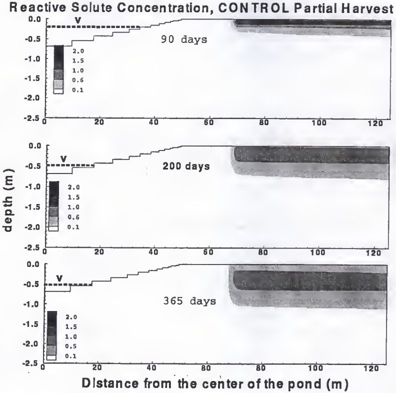

Figure 5.36. Simulated distributions of reactive solute for the CONTROL treatment.

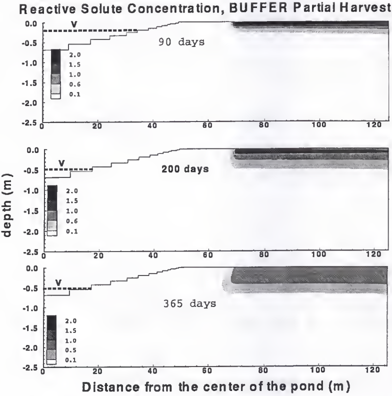

Figure 5.37. Simulated distributions of a reactive solute for the BUFFER control.

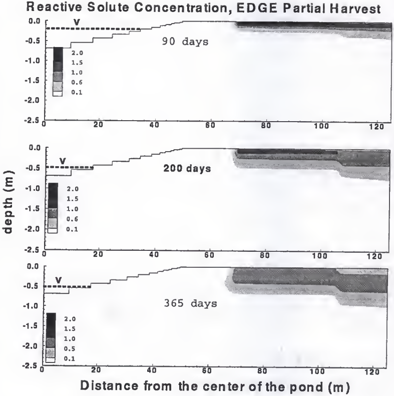

Figure 5.38. Simulated distributions of a reactive solute for the EDGE treatment.

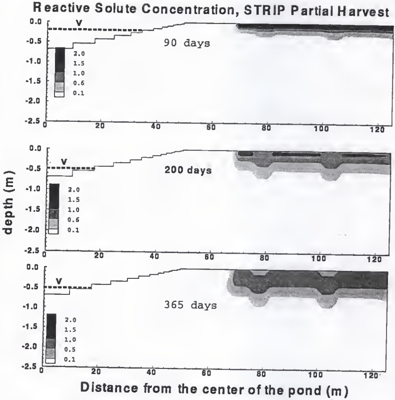

Figure 5.39. Simulated distributions of a reactive solute for the STRIPS treatment.

solute movement as compared to the harvested area of the flatwood forest. The depressed water table at these strip locations resulted in deeper displacement of the solute through the soil profiles. By the end of the simulation (365 days), a solute front of 0.1 mg l^{-1} concentration reached 1-m depth of the subsurface. However, in the harvested part of the flatwood forest, the solute plume trailed behind at 0.6 m from the soil surface.

The solute plume for the EDGE partial harvest was similar generally to the solute plumes for the previously discussed partial harvest (BUFFER, STRIPS, CENTER). The solute moved deeper in the soil profiles in the unharvested pine forest area of the flatwood (Fig. 5.40). Contour areas of the same concentration in both the harvested and unharvested parts of the flatwood were still connected at the end of the simulation. Solute plume concentration, in the unharvested part of the flatwood, of 0.1 mg l^{-1} reached a depth of 1.1 m by day 365. The solute plume in the harvested part did not move as deep as the solute plume in the unharvested part.

Partitioning of the incoming reactive solute over the various components of the CPFF system was reported in table 5.8 as percentages of incoming solute amount into the system. The major part of the incoming solute was adsorbed by the organic content of the upper soil profiles, since throughout the different partial harvest scenarios 85.3 to

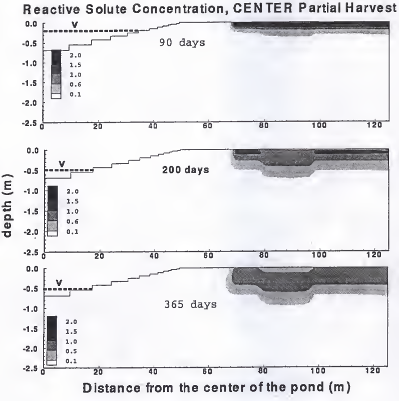

Figure 5.40. Simulated distributions of a reactive solute for the CENTER treatment.

87.2% of the incoming solute was partitioned into the sorbed phase at the end of the simulations. Thus, only 12.6 to 14.3 % of the incoming solute was left in soil solution at the end of the simulations for all of the harvesting scenarios.

Table 5.8. Reactive solute partitioning throughout the system for a M&M weather year.

Partial Harvest	Sorbed solute (%)	Soil Solution (%)	Outflow (%)	Pond (%)
CONTROL	85.3	14.3	0.0	0.001
BUFFER	87.2	12.6	0.1	0.001
EDGE	85.4	14.2	0.2	0.01
STRIPS	86.0	13.6	0.2	0.01
CENTER	85.2	14.0	0.2	0.01

Outflow from the surface water in the pond transported 0.2% of the incoming solute for the EDGE partial harvest and only 0.2% for the BUFFER, STRIPS and CENTER partial harvest scenarios. Because the unharvested CONTROL treatment did not have surface outflow out of the pond no solute was lost from the system. A relatively small percentage of solute (0.001 to 0.01%) was in the ponds for the different harvest scenarios at the end of the simulations.

CHAPTER 6
DISCUSSION

Protecting ground and surface water resources are major environmental concerns in managing CPFF systems in Florida. The impact of using alternative forests management practices in CPFF systems such as unharvested forest buffer zones upon contamination of cypress ponds by pesticides and fertilizers is of particular interest to the current work. In order to investigate contaminant transport in CPFF systems, one must first investigate the impact of management practices upon the system hydrology. Understanding the dynamic interconnection of the different hydrological components of CPFF under a wide range of input conditions is a prerequisite to improved understanding of the solute movement in the system. Exploration of the hydrology of the CPFF was used to help explore the impact of alterative management practices on the water quality in this system.

Hydrological components of the CPFF system includes ET, surface outflow, rainfall interception, groundwater table movement fluctuation of the water filled surface area of cypress ponds are the main focus of the first part of the discussion. The hydrology of the CPFF is first discussed in this chapter, and is followed by a discussion of the impact of the partial harvesting management practices upon the transport of potential contaminants from the flatwood pine forest to the cypress ponds. Herbicides and fertilizers are commonly applied during management of flatwood pine forests.

The three hypothetical weather years used for 12-month simulations for the CPFF systems covered a wide range of possible combinations between the two main hydrological components of the hydrological cycle for this system. The control harvest scenario (mature CPFF) during a mean PET/P weather year has a rainfall level of 1350 mm yr^{-1} and a PET of 1505 mm yr^{-1}; thus there is a negative net difference (i.e., net water input) between rainfall and PET of -155 mm yr^{-1}. The "cold" and "wet" weather year has a positive net difference (732 mm yr^{-1}) between the total rainfall input (1850 mm yr^{-1}) and the PET (1118 mm yr^{-1}) output from the CPFS. The "hot" and "dry" weather year has a very clear water deficiency of -766 mm yr^{-1}. Obviously, during C&W weather treatments a significant portion of the rainfall input into the system will be lost as surface outflow given the net excess of input water into the system. However, during M&M and H&D weather years (drier conditions), surface outflow from these systems should be very limited. The M&M weather considered to be the norm and C&W and H&D weather years are extremes.

EVAPOTRANSPIRATION (ET)

Annual Evapotranspiration

The annual simulated ET for the control treatment is well within the range of that observed experimentally in the field and reported in the literature. Annual ET estimated from a cuvette-based study in a CPFS during a dry year (1070 mm yr^{-1}) was 1270 mm yr^{-1} (Brown, 1981). ET rates for a normal or a wet year would be expected to be higher (Ewel and Smith, 1992). In a recent field experiment in north central Florida, Sun (1995) estimated an annual ET including interception as high as 1265 mm yr^{-1}. In a more intensive experiment on the same site, Liu (1996) reported annual ET values ranging from 767 mm yr^{-1} to 1204 mm yr^{-1} with an annual average rate of 1080 mm yr^{-1}. Results of a sensitivity analysis conducted by Liu (1996) using input data from the same site showed annual ET rates as high as 1400 and 1200 mm yr^{-1} for cypress pond and pine flatwood, respectively. Annual ET rates simulated during the current work fall within the range of variability encountered in the field. Annual ET values simulated for an unharvested CPFF system (control) were 1063, 1251 and 1280 mm yr^{-1} for C&W, M&M and H&D hypothetical weather conditions.

During model simulations total clear cut harvest of all pine and cypress trees decreased ET by 40% on average as compared to the unharvested control for the three hypothetical weather conditions C&W, M&M and H&D. The large decrease in ET associated with tree removal increased the surface outflow out of these systems and water table elevations in both the pond and flatwood. Riekerk et al. (1996) reported a 28% decrease in ET for a totally clear cut CPFF in north Florida. Simulated harvest of only cypress trees resulted in a 30% decrease in ET in comparison to a 20% reduction in ET due to cypress tree harvest during the first few months as reported by Riekerk et al. (1996). Harvesting pine trees from the flatwood forest resulted in a 20% reduction in simulated ET as compared to the control. However, partial pine harvest treatment provided the second highest simulated ET level (10% decrease in ET) after the unharvested control. Since ET is the main hydrological output from these systems (Liu, 1996), the 75% partial harvesting treatment provided lower simulated outflow than the other harvesting treatments with the exception of the control. From the simulated ET results, the partial harvest treatment with the unharvested buffer zone around the pond appears as a practical candidate for an alternative forest management practice.

Daily Evapotranspiration

Evapotranspiration in the CPFF is influenced primarily by the transpiration patterns of its two main tree species: the deciduous cypress trees that do not transpire during winter time and the coniferous pine trees that continuously transpire year around. In addition, climatological variations, such as high PET in the summer vs. low PET in the winter, result in fluctuations of daily ET rates throughout the year. Results of simulated daily ET for the three hypothetical weather years (C&W, M&M, and H&D) are discussed in the following three cases.

Case#1 "Mean" PET/P year (M&M weather)

For the M&M weather years, low ET levels (0.4 - 1.2 mm d^{-1}) simulated during the winter months occur within the range of ET reported in the literature (Liu, 1996). These low ET rates are determined by the low atmospheric demand imposed on the system; in addition, cypress trees as deciduous plants, do not transpire in winter months. During the growing season as the PET increased and cypress trees develop leaves and begin transpiring, simulated ET for all harvest treatments increased to higher levels with increasing time. A maximum rate of 5.2 mm/day for the unharvested control was reached during April/May of the simulated year. The seasonal simulated pattern closely resembles the pattern of ET measurements reported for a CPFF in north-central Florida (Liu, 1996; Heimburg, 1984), where highest values were recorded in April and May and lowest values were reported in January-March. Data from a young pine plantation conducted in north central Florida (Riekerk, 1985) reported the highest monthly ET of 150 mm /month equivalent to 5 mm d^{-1} for the month of May.

Case#2 "Hot" and "Dry" year (H&D weather)

For H&D weather, harvest treatments were characterized with a high imposed PET. The highest simulated ET rate, 6.1 mm d^{-1}, occurred for the unharvested control treatment for the H&D weather during April and May. Ewel and Smith (1993) reported measured daily ET rate in CPFF of 6.8 mm d^{-1} in April and June. An upper limit of 6 mm d^{-1} has been suggested for transpiration in conifer forests (Whitehead and Jarvis, 1981). Most of the harvest treatments were not able to satisfy the imposed high PET demand during H&D weather because of the low rainfall (850 mm yr^{-1}) level imposed on them. In the WETLANDS model, simulated ET is controlled by two factors: atmospheric demand (PET) and availability of water in the root zone. If there is available water in the root zone, the PET is met; otherwise, ET is limited by soil water storage. For H&D weather, high PET over the first 5 months of the year (January through May), and low rainfall depleted a large portion of the soil water storage and the plants could no-longer satisfy the transpiration demand imposed by the PET. Thus, ET may decrease rapidly in a short period of time in the absence of rain. However, with the occurrence of rainfall events, soil water becomes available for plants and ET increases rapidly over time. This scenario of rapid changes in ET over short times occurred for all the treatments; however, it was more frequent for the pine flatwood harvest treatment (PINE). To explain this, it is important to remember that young pine trees and annual plants were assumed to occupy the harvested flatwood area in the PINE treatment and these plants were forced to extract water from the top 1 m of the system as compared to 2.5 m for the unharvested pine trees. In contrast, unharvested control (CONT) and cypress-harvested (CYPR) treatments have mature pine trees over the whole flatwood and consequently are able to uptake water from 0-2.5 m depths in the soil. Thus, ET rates for CONT and CYPR treatments showed a decrease only toward the end of the simulation when the deep soil water storage was depleted. The partial harvesting treatment (PART), was the most efficient treatment since it experienced no major reduction in ET rates during the entire simulation.

Case#3 "Cold" and "Wet" year (C&W)

During C&W weather, daily ET simulated for the harvest treatments followed very similar patterns as for the M&M year but at decreased levels. This reduction in the ET was mainly due to the lower PET imposed on the simulated system. Consequently, water was always available for plants in all the treatments. The net water input for C&W weather was considerably larger than for M&M weather. The curves for daily ET for this year type were relatively smooth and did not experience periodic decreases indicating no significant water storage deficiency as were encountered in the H&D weather.

Rainfall Interception

Interception is directly related to rainfall intensity and LAI of the stand. Thus, high interception rates are expected from cypress trees especially during dry years and low interception rates are expected from pine trees during wet years. A high interception percentage, 24% of rainfall, was simulated for cypress trees during the "dry" year conditions. The lowest interception percentage was simulated for pine trees during "wet" year conditions. Similar results have been reported from field experiments. Experimental rainfall interceptions of 266 mm (20% of the rainfall) in ponds and 215 mm (15% of the rainfall) in flatwood forest were not significantly different (Liu, 1996). Other field studies (Heimburg, 1984) reported an interception percentage of 25% of incoming rainfall for a similar landscape. More variation has been reported from field experiments for the interception percentages ranging from 9% in Ivory Coast for a Tai forest to 33% for Pinus radiata in New Zealand (Wells and Blake, 1972). Simulated interception results for the different treatments at the forest level, where both pine and cypress trees are present on the same CPFF, were as high as 28% during a "dry" year for control treatments, and as low as 4% during a "wet" year for the total "clear cut" harvest treatment. Since the other simulated treatments have LAI values within the range of the control and the total clear cut treatments; their interception also occurred between 24% and 4% of the rainfall. Total "clear cut" harvest not only caused a severe reduction in ET but also received more rainfall than the other treatments given its low interception capacity. Obviously, the additive effects of the transpiration reduction and lower interception capacity partially explains the high water table elevation simulated for this treatment. The unharvested control treatment had the highest rainfall interception and partial harvesting had the second highest interception percentage.

Surface Outflow

Surface outflow occurred from simulated ponds once the water in the pond reached an imposed critical level (0.2 m from the soil surface). No water input from adjacent upstream ponds was allowed during simulations. Ponds that do not receive any input from adjacent ponds have been reported in the literature (Riekerk et al., 1996; Sun, 1995). Most ponds experiencing runon into them lose comparable surface water as outflow from an opposite part. Consequently, the effect of runon of such ponds is offset by outflow out of them. Sun (1995) reported a difference between runon and outflow for the same pond ranging from less than 1% to 4% of the total water input.

During C&W weather, all the treatments experienced outflow due to the positive net water input. These results were expected since the harvest treatments experienced a significant ET reduction during C&W weather as compared to "M&M" and "H&D" weather conditions. Annual outflow from the treatments of "C&W" ranged between 532 mm to 1081 mm for the unharvested control and the total "clear cut" harvest treatments, respectively. Total clear cut (TOT) had the highest outflow level during any weather conditions followed by the cypress harvest treatment. The flatwood harvest pine treatment was next. The partial harvest treatment produced only half the outflow produced by the pine harvest treatment. Clear cutting (TOT) the flatwood generated surface outflow regardless of the weather year type. Observed results from a long term watershed in north Florida (Riekerk, 1989) showed a 150% increase in surface outflow the first year after clear cutting of flatwood forest for the highly disturbed treatments.

Surface outflow out of the simulated system occurred mainly during December-March period with low ET; however, some outflow took place during the summer months which is the wet season for north central Florida. The resultant effects of ET and rainfall caused the initiation of surface outflow. However, from the simulated results, it is clear that outflow is more likely to occur during a low ET demand portion of the year regardless of the rainfall amount. Similarly, results from field experiments in north Florida (Sun, 1995) indicate that most surface flow occurred during January-March (winter season) when the water table levels were high and cypress ponds were full. Sun (1995) further stated that moderate rainfall in winter when ET was the lowest for the year could generate significant outflow; however, high rainfall in summer time, when ET is the highest for the year, might not generate surface outflow.

Pond and Ground Water Elevations

Simulated results showed that the groundwater elevations in the flatwood forest tend to fluctuate much more than pond water elevations. The ratio of fluctuations of pond levels to that of groundwater levels can be as high as 5:1. This effect can be related mainly to the low storage capacity of soil in the flatwood forest as compared to surface water in the pond. An equal loss of 1 mm of water from the pond and subsurface results in a 1 mm decrease of the surface water level in the pond and several mm decrease of the groundwater table in the flatwood. Another explanation for this difference in water level variability between the pond surface water and the groundwater in the flatwood had been postulated by Sun (1996). That hypothesis states that more ET occurs from pine trees in flatwood forests than from cypress trees in the ponds could explain the higher water table fluctuation as compared to cypress pond. More ET loss by pine trees would explain more water table drop in the flatwood. This hypothesis has been shown to be invalid over an annual period, since annual ET for Cypress ponds and flatwood pine forests were shown to be significantly not different (Liu, 1996; Riekerk et al., 1995). However, seasonal differences in ET between the two systems may be important (Sun, 1995).

Simulated patterns for pond and ground water levels for the partial harvest pine trees in a flatwood forest were very similar to those of the unharvested control treatment. However, the magnitudes of variability of water level(increase or decrease) were more prominent in the unharvested control treatments than in the partial harvesting treatments. Total clear cut simulations were characterized by the complete absence of deep-rooted trees that are able to uptake water from deep soil profiles. In total clear cut, only annual and young pine trees have shallow root systems, that can only explore water in the upper 1 m. Consequently, reduced ET, lower rainfall interception and shallow root systems resulted in high pond and flatwood ground water levels during the entire simulations for total "clear cut" harvesting. This demonstrates the major role that ET plays in the hydrology of the CPFF and consequently, the movement of potential contaminants within this system.

Spatial Distributions of Pond and Ground-Water Elevations

Contaminant transport in porous media is primarily driven by the mass flow of water through the system. Temporal and spatial changes of the shape of the ground water table provide an indicator of water flow through the porous subsurface domain. Spatial distributions of the ground water table in the flatwood were influenced by climatological differences with time of year (winter vs. summer) and tree harvest. The ground water table in the flatwood was higher than the pond water level during periods of low ET demand, (late fall and winter time). This relatively high water table in the flatwood area induced water flow movement from the flatwood to the pond (i.e., groundwater discharge) and since the pond was already full, this excess (outflow) water was assumed to flow to a nearby pond or stream. The spatial shape of the ground water table for any given time indicated the location of the partial harvesting. Unharvested zones in partially harvested pine forests had lower ground water tables as compared to its surrounding as a result of transpiration. Beginning in the spring, water flowed from the pond into the flatwood pine forest for all harvesting scenarios for a M&M and H&D weather years.

The beginning of each simulation (January 1) coincided with low imposed PET; however, as the simulations progressed through the simulated year, the PET demand increased and consequently the pond and ground water levels decreased substantially from earlier high levels. This drop was accentuated within and around the location of the unharvested pine zone. Thus, since actively transpiring pine trees within the unharvested buffer zone in the (BUFFER) treatment were located adjacent to the pond, a drop of the ground water level occurred near the edge of the pond. The ground water level rebounded back to a higher level with increasing distance from the buffer zone. Similar to the BUFFER treatments, the remaining other partial harvest treatments (EDGE, STRIPS and CENTER) showed an obvious drop of the groundwater table level at the location of the unharvested part of the systems. These regions of low ground water level corresponded to the spatial location of the deep rooted pine trees. The shape of the water table was obviously influenced by the location of the unharvested pine trees.

Water flow simulations under a mean weather year (M&M) revealed water levels in the pond and ground water table to be high during the late fall and winter time. Flatwood groundwater elevations were sometimes higher than the water level in the pond and the frequency increased substantially during weather years with high rainfall and or low ET demand (C&W). This was especially evident after clear cutting of the pine flatwood and/or the cypress pond. However, during periods of high ET demand within a given year for average weather (M&M) conditions, ground water table is relatively lower than the previous case. Differences between the pond water level and groundwater in the flatwood became larger during dry periods.

To illustrate the variable water movement between the flatwood and the pond, water flow vectors in the horizontal and vertical directions were used to compute water "particle" trajectories, called streamtraces, through the simulated domain. The stream function is a mathematical device to describe a flow concisely by its streamlines (Le Méhauté, 1976). Le Méhauté (1976) added that the stream function may be used to calculate many kinds of flow for incompressible fluid through porous medium: steady or unsteady and two-dimensional or three-dimensional. In practice, stream functions are mainly used in steady two-dimensional flow (Le Méhauté, 1976). Streamlines or flowlines represent paths along which water can flow through a cross section (Cedergren, 1988). For steady flow, streamlines are not altered with time. However, for transient flow, streamtraces undergo alterations in space with increasing times. Streamlines intersect at right angles with equipotential lines through the flow domain for isotropic media (Cedergren, 1988).

Streamtraces were plotted using Tecplot 6.0 for two treatments -total harvest and unharvested control- in order to demonstrate details for subsurface water flow during cases of net flow to and from the flatwood and the pond. Streamtraces shown here for water flux components in simulations for CPFF systems represent instantaneous fluid flow paths developed under conditions of transient flow in variably saturated subsurface porous media. They do not represent true streamlines. In other words, these streamtraces represent "photographs" taken at specific times. Figure (6.1) shows that for a M&M weather condition and for a CONTROL harvest treatment, water flows from the flatwood into the pond (i.e., groundwater discharge) during the winter time due to gradients of hydraulic head. However, during the summer time the pond recharged the flatwood (Fig. 6.2). Streamtraces in Fig 6.2 show arbitrary fluid flow paths as surface water in the cypress pond subirrigate the surrounded pine forest in response to hydraulic head gradients.

These hydrological findings demonstrate that surface water contamination does not pose a problem during mean (M&M) or dry (H&D) weather conditions for partial harvest of the pine forest and that solute movement to the pond occurs only during periods of high water table when net water flow occurs from the flatwood to the pond.

Solute Transport in the CPFF

A major obstacle in studying contaminant transport in CPFF systems in the field is the complexity of the surface and subsurface flow domains and a limited understanding of the interdependence of the different hydrological parameters of the system. The water flow simulations revealed that during times of high water table there is a tendency for the water to flow from the flatwood toward the pond (i.e.,

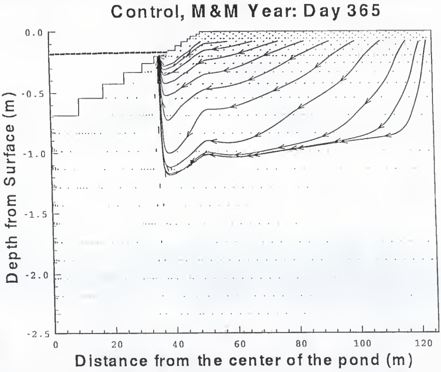

Figure 6.2. Streamtraces for a control (unharvest) treatment during M&M weather conditions: day 365.

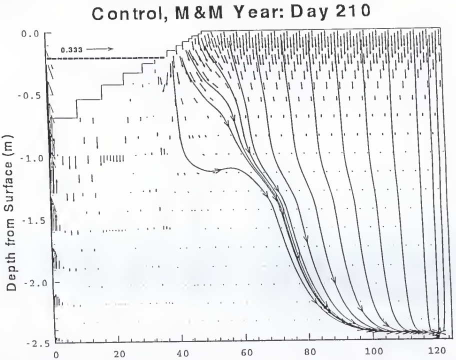

Figure 6.1. Streamtraces for a control (unharvest) treatment during M&M weather conditions: day 210.

groundwater recharge). This tendency toward groundwater recharge is stronger during a "wet" year than for a "mean" or "dry" weather year. Individual cypress ponds tend to shrinks in size during periods of groundwater recharge and expand during groundwater discharge.

Discussion of contaminant transport focused on two main parts. The first part discusses the case of a non reactive solute with and without plant uptake. The second part of this discussion is about a reactive solute without plant uptake.

Nonreactive Solute Tracer Transport Without Plant Uptake

During the M&M weather conditions, for all five harvest treatments, contaminant transport occurred in the direction of the pond during the winter simulated period and by day 90 the contaminant had already reached the pond. Afterwards, as the ground water table in the forest receded vertically downward through the domain, the solute moved downward also. In the unharvested control treatment with deep pine roots in the flatwood, groundwater table level dropped uniformly across the system; consequently, the solute plume had spread over a larger portion of the flatwood by the end of the simulation. Because the solute plume was spread over a large subsurface area, the maximum solute concentration in the subsurface flow domain was not as high as in the plumes of some of the partial harvest treatments. However, transpiration gave larger solute concentrations in the soil solution than in the input solution at the soil surfaces.

The unharvested buffer zone adjacent to the pond, in the case of the partial harvest BUFFER treatment, created a hydraulic gradient that moved the water table at the location deeper into the soil profile than the shallow-rooted regeneration zone. The solute plume reached this active buffer zone by day 90, as ET increased to its highest levels, the buffer zone intercepted the solute since lateral flow dominated the system during the winter time. The buffer zone forced the invading solute front to avoid the pond and forced it downward to deeper depths. Thus, the buffer zone protected the pond and the area underneath it from the invading subsurface contaminant as water moved toward the pond. Because this solute is not absorbed by plant roots, a relative low concentration (6% of the original concentration) was left in the soil solution at the edge of the pond.

The solute plume was differentially influenced spatially during the simulations in all the partial harvesting treatments. Plant roots in the unharvested zone for the partial harvesting treatments were distributed over soil profiles 2.5 times that of the shallow plant roots (1.0 m) in the regenerated zone that underwent harvest of pine trees. As lateral plumes of contaminant moved downward, the transport was relatively faster in the porous media beneath unharvested areas than under harvested areas.

Nonreactive Solute Transport With Plant Uptake

Solute plumes for these harvest treatments showed similar trends as those of the treatments for solute without plant uptake except that maximum solute concentrations were considerably less. The solute plumes for these treatments spread less than those of the previous case when solute uptake by plant roots was not simulated.

During M&M weather conditions, solute absorbed by the plants accounted for 71 to 76% of the applied solute to the system. Because both solute lost through surface outflow and solute stored in the pond were insignificant (less than 0.1 % of the added solute to the system), the remaining solute 24 to 29% of applied solute was located mainly in soil water storage for BUFFER and CONT treatments, respectively. In all the harvest treatments, solute molecules moved below the reach of the short-rooted plants in the harvested part of the domain. However, the root systems for unharvested the pine and cypress trees were forced to the bottom of the subsurface flow domain. It can be inferred from this that single applications of large amounts of fertilizers (such as NO_3-N) are more vulnerable to leaching from a relatively shallow uptake zone than from a deep root zone. Thus, multiple applications of fertilizers could be applied over the growing season to avoid excessive solute leaching. Riekerk (1988) supports the idea of forest fertilization since he found, in a field study, that only some of the applied NH_4^+-N have reached the open water through the soil fairly soon during the first year after its application. He added that this mobile cation was absorbed by rapidly developing pine plantation; consequently, it was not detected in the surface outflow after the first year.

Reactive Solute (Atrazine) Without Plant Uptake

The relatively high organic content (4 %) of the top flatwood forest soil layer influenced Atrazine movement within the CPFF. At least 85% of the solute present in the system was sorbed to the organic content of the top soil layers. Solute movement was severely retarded due to the sorption. After one-year of simulated time, solute plumes were only able to reach 1-m of depth in the unharvested flatwood pine of the CPFF. Riekerk (1988) suggested that ground applied potassium and phosphate (reactive solutes) move slowly through the soil as compared to the mobile NH_4^+-N.

As seen for transport of the nonreactive solutes, solute plumes in the unharvested pine flatwood areas for all partial harvest scenarios (BUFFER, EDGE, CENTER and STRIPS) moved deeper than solute plumes in the harvested area of the flatwood forest. Deep root systems for the coniferous pine trees in the unharvest part of the flatwood area were able to explore the available water in the entire subsurface flow domain (2.5 m) and consequently depressed the water table deeper than the short root systems for the harvested area of the flatwood. The deeper water table movement in the unharvested part of the flatwood was accompanied by a movement of the reactive solute present in the soil solution.

Only a very small portion of the applied solute to the system moved into the pond surface water throughout the one-year simulations during M&M weather. The percentage of solute lost with surface outflow from the pond was almost the same for all partial harvest scenarios. Similarly, the percentage of solute left in the pond at the end of individual simulations for the partial harvest scenarios were not greatly different. Results from this research agree with other field researches (Riekerk, 1988) about the need for more detailed field studies of solute movement (reactive and nonreactive) in CPFF systems to give more insight about this subject.

CHAPTER 7
SUMMARY AND CONCLUSIONS

Cypress ponds in flatwood pine forest systems of north central Florida perform several important functions in the landscape, including storage of surface water, aquifer recharge, sub-irrigation of flatwood forests during much of the year, and providing diverse plant and wildlife habitat. During periods of high rainfall and low PET, surface drainage of the landscape occurs as surface runoff moves through strands of cypress ponds to discharge excess water to local streams and rivers. Considerable concern has arisen over potential ecological and environmental impacts of forest management practices such as tree harvest upon the structure and function of these landscapes. A number of experimental investigations are reported in the literature for acquiring information essential to forest management, conservation and regulatory decisions. Impacts of some management practices such as clear-cut harvesting may range from a few months to several years. Unfortunately, field investigations are typically site- and weather-specific. Thus, total reliance upon results from field experiments requires a very large resource base acquired over a long time span.

Numerical hydrological models offer a practical tool for optimizing two finite research assets, time and money. Modeling endeavors may be used to lessen the number of required field experiments, assist in planning specific experiments, and underscore important parameters and variables that most influence this system. A combination of carefully planned field investigations and physically-based hydrological models offers an effective means to make informed analyses and/or predictions concerning these sensitive environments.

The hydrological model, WETLANDS, provides a multi-dimensional model for water flow and solute transport through variably-saturated porous media. This model features dynamic linkage between surface water in a pond that fluctuates seasonally in size to water in surrounding subsurface soil and ground water has recently been developed. WETLANDS was used in this dissertation to investigate the impact of alternative forest harvesting practices on commercial pine forests in coastal plains flatwood areas over a wide range of climatological conditions. WETLANDS permitted investigation of the influence of weather (PET and rainfall) upon complex interactions involving major hydrological processes that occur in the critical interface between cypress ponds and surrounding flatwood pine forests. Field data from individual cypress wetland ponds located in pine flatwood in north central Florida were used to successfully validate the model. Simulated results for plant transpiration, surface water levels in a fluctuating pond, and ground water table depth in the flatwood forest compared well with reported measurements in spite of simplifying assumptions utilized in simulations.

Simulations were first performed to determine the influence of three annual weather patterns- C&W, M&M and H&D- upon water flow and solute transport in the subsurface for a cypress pond located in a flatwood forest with mature pine trees. Simulations were performed to determine the influence of selected harvesting scenarios upon water flow and contaminant transport in the subsurface during C&W, M&M and H&D weather patterns. Five harvesting scenarios were investigated: unharvested full stand (CONT), pine tree harvested (PINE), cypress tree harvested (CYPR), partial pine tree harvested (PART) and total clear-cut (TOT) of both pine and cypress trees. Three levels of PET based upon temperature were used: "hot" (PET= 1616 mm yr^{-1}), "mean" (PET= 1505 mm yr^{-1}) and "cold" (PET= 1118 mm yr^{-1}). Three rainfall levels were used : "wet" [1850 mm/year], "mean" [1350 mm/year], and "dry" [850 mm/year]. Three combinations of PET and P were selected to provide three hypothetical weather years ("hot" & "dry" (H&D), "mean" PET & P (M&M),

and "cold" & "wet" (C&W)). Potential net water input (NWI=P-PET) for C&W, M&M, and H&D weather years were +732, -155, and -732 mm yr^{-1}. Model simulations revealed that the hydrology of CPFF systems is dominated by the potential net water input (R-PET). Because of the lower water storage capacity of the flatwood soil matrix as compared to the pond, simulated depths of groundwater tables in the flatwood underwent greater fluctuations than surface water in the pond. During wet periods (summer and winter) for any weather year, the groundwater tables tend to be high and surface runoff from the flatwood area occurred through the pond to neighboring ponds or streams. However, when the water table of the surrounding pine flatwoods dropped below that of the cypress ponds during dry periods, water in the pond tended to subirrigate (i.e., groundwater recharge) the soil for some distance into the flatwood forest.

For all weather years, surface runoff was strongly related to the annual rainfall level and the degree of tree removal from a mature tree stand during harvesting. As expected, runoff occurred during the wet seasons (winter and summer) when net water inputs were high and shallow water tables occurred. Total tree harvest of both pine and cypress trees from the system generated the highest surface runoff followed by the treatment where only the cypress trees were harvested. Utilization of an unharvested buffer zone (25% of flatwood forest) during 75% partial pine harvesting substantially reduced surface runoff.

During all simulations, rainfall interception was directly related to rainfall level, LAI of the stand and the specific harvesting scenario. Higher interception occurred during dry years than wet years for a given harvesting scenario or plant species since the limiting factor in such cases is the rainfall amount.

The use of an unharvested buffer zone around cypress ponds during partial harvesting (leaving 25% of the flatwood pine) showed promising environmental results such as decreased surface runoff, increased ET and lowered groundwater table depth in as compared to total harvest of flatwood pine trees. Simulations revealed that the groundwater table depth in the flatwood was influenced by the physical location of the unharvested pine over the flatwood.

Solute transport in cypress pond flatwood pine systems has received very little attention experimentally or theoretically relative to water flow. Because herbicides and fertilizers are commonly applied to commercial pine forests in flatwood regions, they are generally considered as potential contaminants for surface water in cypress ponds. Experimental investigations of the transport of potential contaminants into cypress pond flatwood pine systems are greatly dependent upon such factors as: illdefined physical boundaries of these topographically flat systems, heterogeneity encountered in the soil layers below the ground as well as heterogeneity of plant species above the ground, difficulties in accounting for all processes taking place in the field such as sorption/desorption, degradation, uptake by plant roots and precipitation, and the high cost of running such experimental studies. Because of these and other factors, WETLANDS model provides a convenient scientific tool for obtaining insight into solute transport in such complex systems.

Model simulations revealed that contamination of surface water in fluctuating cypress ponds primarily occurred from the flatwood pine forest into the pond. However, during most months of the year contaminants were not transported to ponds since water flow occurred away from the pond into the pine forest. Groundwater table movement in space and time was shown to give fundamental insight into the solute movement within the system. Earlier Crownover et al. (1995) reported that water flow in the interface between cypress ponds and flatwood pine forests can occur toward the pond, away from the pond, and through the pond. The direction of net water flow in the interfacial zone was shown in these simulations to greatly limit the potential impact of herbicides and fertilizers upon contamination of cypress ponds. The solute movement in this system was highly dependent on whether the solute is absorbed or not absorbed by plant roots. Without uptake by roots, solute spread over larger soil domains and greatly increased maximum concentrations within plumes of solute than when uptake was considered. One year simulations revealed, maximum concentrations of solute to be as low as 30% of the initial concentration when uptake by plant roots was considered; whereas, maximum concentrations without plant uptake of solute were as high as 3 times that of the applied concentration.

As expected, the yearly rainfall level influenced the solute movement within the system. A "wet" year resulted in 15% of the applied solute reaching the pond. However, during an average rainfall year less than 1% of the applied solute reached the pond. Thus, contaminant transport from the pine forest into cypress ponds is obviously not a major problem during years average of less than average rainfall.

The movement a reactive solute in the CPFS was drastically reduced by the sorption process into the high organic content of the top 20 cm soil layer of the flatwood pine forest; since at least 85% of the solute present in the system was sorbed to the organic content of the top soil layers. At the end of a one year long of simulated time, solute plumes were only able to reach 1 m of depth in the unharvested flatwood pine of the CPFS.

Solute plumes in the unharvested pine flatwood areas for the all partial harvest scenarios (BUFFER, EDGE, CENTER and STRIPS) moved deeper than solute plumes in the harvested area of the flatwood forest.

Relatively, there was a very small portion of the applied solute to the system that did move into the pond surface water throughout the one year long simulations. The solute portion lost with surface runoff from the pond was almost the same for all partial harvest scenarios. Similarly, the solute portion left in the pond at the end of the individual simulations for the partial harvest scenarios was not different.

Eventhough, solute plumes in both the harvest and unharvest areas of the flatwood pine forest moved with different speed through the simulations; during the entire simulations, contour areas of the same concentration in both areas were connected and did not rupture from each other as it was in the case of the nonreactive solute.

APPENDIX

APPENDIX
INPUT PARAMETERS FOR SIMULATIONS

Soil Layers

Soils of the cypress pond flatwood pine area are typically spodosols. Two Typical soil series characterize this system, Pomona sand (Sandy, siliceous, hyperthermic Ultic Haplaquods), and Monteocha loamy sand (Sandy, siliceous, hyperthermic Ultic Haplaquods) (National Cooperative Soil Survey, 1982).

The Pomona series consists of very deep, poorly drained soils originally formed in sandy and loamy marine sediments. The soils of the Pomona series have a very dark gray sand surface layer underlain to a depth of 0.7 m by layers of gray and light gray sand. About 0.35 m of very dark gray sand is coated with organic matter occurs underneath. Brown sand occurs between 0.9 to 1.3 m depths. Below 1.3 m and extending to 1.85 m or more is gray sandy clay loam or light sandy clay.

In a representative profile of Monteocha series, the surface is black loamy sand about 30 cm thick. The subsurface is light brownish gray sand about 15 cm thick and the subsoil is dark brown sand 40 cm thick. Underneath is 35 cm of brown fine sand overlying fine sandy loam. Between 215 and 240 cm depth light gray sand occurs. Cutright (1974) studied the geology of a cypress pond flatwood system and reported a gray blue sandy-clay with extremely low hydraulic conductivity occurs between 250 to 300 cm depth.

Four main soil layers (Fig. A.1), were represented in these simulations. An organic layer was also placed along the bottom of the pond. Thickness for each of these four layers are specified as spacial variables. The first layer represents the upper 40 cm of the soil profile and includes sandy (A, and E horizons) porous subsurface material. A spodic horizons (Bh1 and Bh2 horizons), with average thickness of 45 cm is underneath. A third layer of 20-cm thickness is represented by E'and A' horizons. A fourth layer 140-cm thick is represented by a thick argillic horizon (Bts).

Soil Hydraulic Conductivity

Average saturated hydraulic conductivity K_{sat} values for each of the four main subsurface layers identified in the previous section in addition to a soil layer rich in organic matter in the bottom of the pond are presented in Table (A.1). These values were calculated based on data found in The Alachua County Soil Survey and investigations conducted by van Rees (1984) and Philips et al. (1989) in a Spodosol flatwood area.

Data for soil water retention for these soil layers were described for laboratory conditions by Philips et al. (1989). Curve parameters were obtained by least square fitting the retention data using the analytical model of van Genuchten (1978). Input parameters for the analytical model

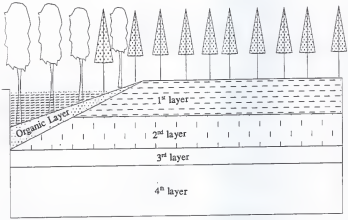

Figure A.1. Schematic of the different soil layers of the simulated CPFS.

of van Genuchten for each of the soil layers of this system are presented in table A.1.

Table A.1. van Genuchten parameters for soil water retention.

Layer	Θ_s[1] ($cm^3\ cm^{-3}$)	Θ_r[2] ($cm^3\ cm^{-3}$)	α[3]	n	K_{sat} ($cm\ h^{-1}$)
First	0.400	0.110	0.032	2.96	30
Second	0.460	0.210	0.015	3.84	06
Third	0.350	0.070	0.019	3.84	10
Fourth	0.350	0.070	0.021	3.64	02
Pond Layer	0.606	0.001	0.012	1.19	40

Plant Root Distributions

van Rees (1984) quantified the vertical root distribution of slash pine (Pinus elliotii Engelm. var. elliottii), saw palmetto (Serenoa repens) and other understory species to a depth of 2.4-m depth on a poorly-drained Spodosol in north central Florida. He reported that 54% of the total live root length at the site occurred in the upper 40 cm of the soil and another 24% occurred in the 1.4 m thick argillic horizon (Table A.2).

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[1] Θ_s = saturated water content

[2] Θ_r = residual water content.

[3] α and n = van Genuchten parameters of the water retention curve.

Table A.2. Vertical mean root length per surface area.

Soil Depth(cm)	Pine[a]	Palmetto[b]	Understory[c]
	($m\ m^{-2}$)		
0-105	830	300	924
105-245	379	223	25

Cypress trees were arbitrarily assumed in the simulations to have 66% of their root distribution in the first 1.0 m and the remaining 34% in the deeper 1.5-m soil profiles. Root distribution for the annual plants was assumed to be equally distributed in the top 1 m of the soil profile.

Rainfall

Average annual rainfall for Gainesville, FL is 1320 mm (52 inches) per year. A low of 840 mm (33 inches) was recorded in 1917 and a high of 1870 mm (74 inches) was reported in 1953 (Dohrenwend, 1978). Daily precipitation data for Gainesville are available for the last 91 years (1903 - 1994) were generated from the weather record of the Agronomy Weather Station at the University of Florida, IFAS. Daily mean and standard deviations of the precipitation were calculated for each day of the year. A "wet" year, a "mean" year and a "dry" year (Fig. A.2 - A.4) were defined as follows:

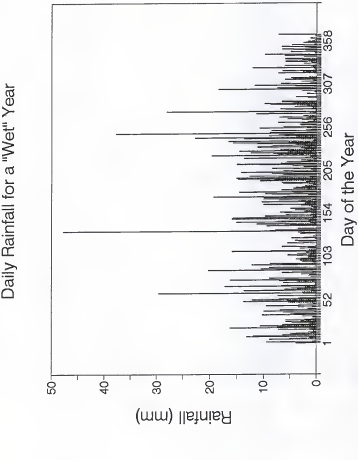

Figure A2. Daily rainfall for a "Wet" weather year at Gainesville, FL

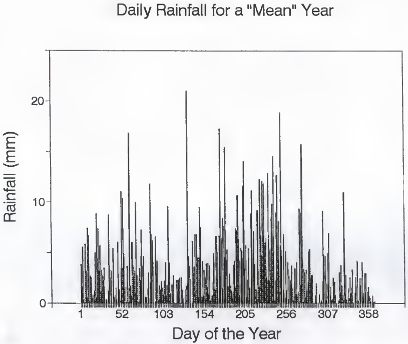

Figure A3. Daily rainfall for a "Mean" weather year at Gainesville, FL

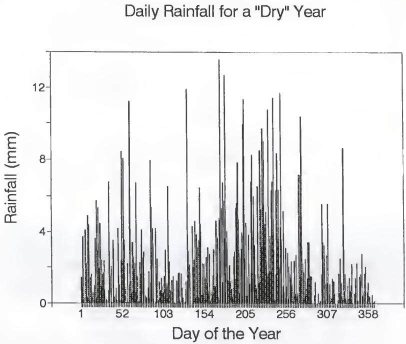
Daily Rainfall for a "Dry" Year

Figure A4. Daily rainfall for a "Dry" weather year at Gainesville, FL

Wet-year

$$P_{Wet} = P_{Mean} + Std.\ Dev.$$

Dry-year

$$P_{Dry} = P_{Mean} - Std.\ Dev. \qquad (A.1)$$

Mean-year

$$P_{Mean} = P_{Mean}$$

Organic carbon content and reactive sorption coefficients

Reactive solutes are partitioned between soil solution and adsorption sites. The primary adsorptive surface for organic pesticides is the fraction of organic carbon in the soil (Fetter, 1993). The values of the sorption distribution coefficients for the reactive solute (Atrazine) for the different soil layers in the system were determined using equation (5.2) and the organic carbon content of the different soil layers (Table A.3). The values for the organic carbon content for the different soil layers were based on work of Carlisle et al. (1988). For simulations of solute transport, the top flatwood soil layer was divided into two soil layers based on the organic carbon content. The top 20 cm has higher organic carbon content than the underlying 30 cm of the soil profiles.

Table A.3. The organic carbon content for the different soil layers used.

	Soil Layers					
	1st	2nd	3rd	4th	5th	Pond Layer
Organic carbon (%)	3.49	1.0	1.0	3.00	0.5	20.0

Atrazine sorption was assumed to follow a linear sorption isotherm for the low concentration used in the simulations. The sorption coefficients, K_d's, for the soil layers present in the system are presented in table A.4.

Table A.4. The sorption distribution coefficients for reactive solute in the different soil layers used.

	Soil Layers					
	1st	2nd	3rd	4th	5th	Pond Layer
K_d (m kg^{-1})	3.49	0.99	0.99	2.99	0.49	19.95

Spatial discretization

The spatial discretization of the simulated system was accomplished through a variable grid size in both the horizontal and vertical directions. The horizontal grid starts with an initial spacing of 0.05 m for the first two columns of the system, then the spacing for each subsequent column equals the spacing of the previous column times the multiplier, 1.25, until the spacing equals 1.0 m, whereupon spacing becomes constant at 1.0 m. Similarly, the initial spacing in the vertical direction starts at 0.01 m then the spacing for each subsequent row equals a multiplier (1.25) time the spacing of the previous row, until spacing reaches 0.1 m, after which spacing becomes constant to 0.1 m. The grid system used for the simulations is presented in Figure

A.5.

The longitudinal and transverse dispersivities were chosen as 0.10 m and 0.01 m, respectively. These values were selected after considering dispersivity values reported in the literature (Gelhar et al., 1992) and accounting for the spatial and temporal discretizations used for the system.

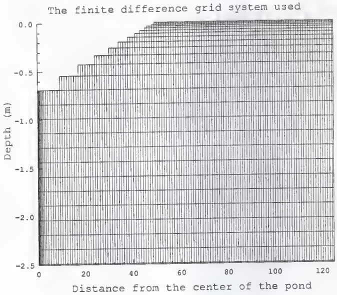

Figure A.5 Spatial discretization for the simulated system.

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BIOGRAPHICAL SKETCH

Ali Fares was born on February 23, 1960 in Manzel Bel Ouaer, Soussa Province, Tunisia. After graduation from Boys' High School of Soussa at age 20, he entered the College of Horticultural Engineering. He graduated with a bachelor's degree in horticultural engineering in 1984. After graduation he accepted a job with the Tunisian Ministry of Agriculture in November, 1984. Simultaneously, he was registered as a graduate student in the Plant Physiology Program at the University of Tunis, Tunisia. He received a post-graduate degree (A.E.A.) in September, 1986. In January, 1988 he started a master's degree program in weed science at the Agronomy Department of the University of Florida. He received his master's degree in December 1990. He started his Ph.D. program in the Soil and Water Science Department of the University of Florida in January, 1991. In December, 1996, he is expected to receive a Ph.D. degree in soil and water science with a concentration in hydrologic sciences and emphsis on soil physics.

He is married to Samira Ben Gadha. They are blessed with four children, Amina, Sara, Othman and Ayoub.

I certify that I have read this study and that in my opinion it conforms to acceptable standards of scholarly presentation and is fully adequate, in scope and quality, as a dissertation for the degree of Doctor of Philosophy.

Robert S. Mansell

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